Thermal Testing: The Basics of Planning, Preparation, and Implementation

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Course Objectives

- Become familiar with a systems engineering approach to thermal testing
- Understand the different types of thermal testing
- Understand the process for planning, preparing, and executing a thermal test including those involving flight hardware
- Understand methods of test environment simulation & temperature control
- Understand the role of analysis in test planning and preparation

A Good Test is Worth 1000 Analyses

- **The operative word is “good”**
  - **A good test is one that singly focuses to meet your primary objectives & accommodates the needs of secondary objectives including functionality**
  - **Primary objectives are synthesized by asking yourself why are you conducting a test?**
  - **Generally, an empirical test is performed to improve your knowledge of some hardware of design aspect**
  - **A poorly conceived test is practically worthless**

Why Do We Perform Tests?

- To characterize parameters that are difficult to quantify analytically
- To characterize design performance/behavior

Typically, non-flight H/W

DEVELOPMENTAL TESTING

- To demonstrate in-specification hardware performance beyond allowable flight temperature range
- To uncover design or workmanship defects

Flight or QUAL H/W

ASSEMBLY PROTOFLIGHT/ QUALIFICATION

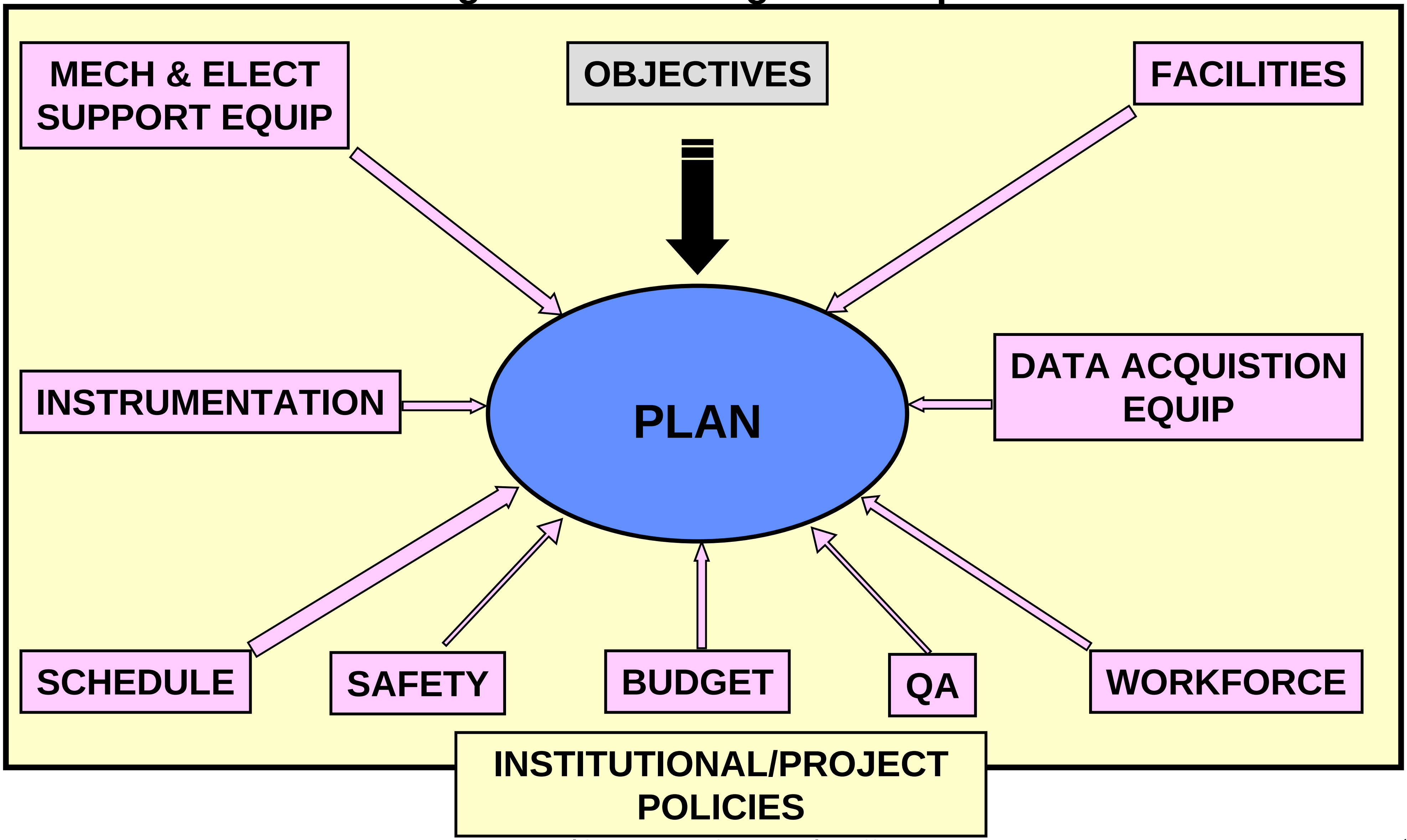
- To validate a thermal design
- To demonstrate functionality at expected temperature

Flight or QUAL H/W

SYSTEM- OR ASSEMBLY-LEVEL THERMAL BALANCE

We Don't Plan to Fail, We Fail to Plan

- At the heart of a "good" test is a good test plan



What Makes a "Good" Test

- **Well defined objectives (primary & secondary)**
- **A test case matrix that directly maps into the objectives**
- **Understanding your role & duties in planning, preparing, executing, and documenting the test**
- **Understanding your resource constraints**
  - **Financial budget**
  - **Schedule**
  - **Facilities including instrumentation & data acquisition**
  - **Mechanical & electrical ground support equipment**
  - **Workforce**
- **Tapping into the test experiences of others**
  - **Conduct peer reviews of your plan & approach**

Types of Thermal Testing

There Are Three General Categories

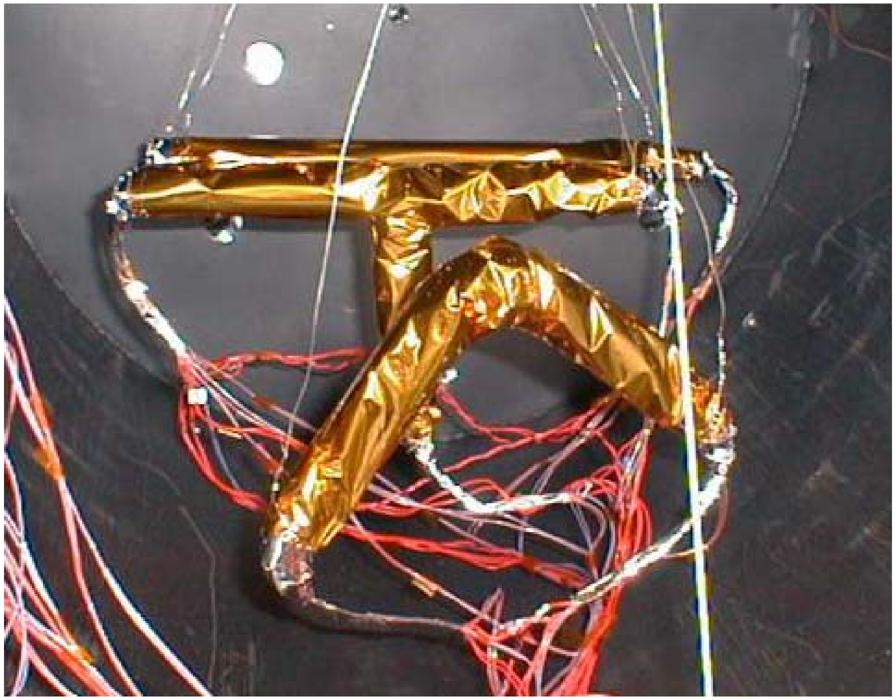
DEVELOPMENTAL TESTING	ASSEMBLY PROTOFLIGHT/ QUALIFICATION OR FLIGHT ACCEPTANCE	SYSTEM- OR ASSEMBLY-LEVEL THERMAL BALANCE
• To characterize parameters that are difficult to quantify analytically • To characterize design performance/behavior	• To demonstrate in-specification hardware performance beyond allowable flight temperature range • To uncover design or workmanship defects	• To validate a thermal design • Empirical validation is the goal • To demonstrate functionality at expected temperatures
• Thermal environment is known • Temperature is a dependent parameter	• Temperature is an independent parameter; specified *a priori* along with dwell times, ramp rate, & number of cycles	• Thermal environment is known • Temperature is a dependent parameter

Thermal Development Testing

- Used to assist design development, especially for situations that are difficult to characterize analytically & <u>are key thermal design drivers</u>
  - Insulation performance, especially MLI blankets
  - Interface contact conductance
  - Bearing conductance
- Used to expand thermal design space beyond a “single point”
  - Investigate if a design approach is feasible (“proof-of-concept”)
  - Determine design sensitivity to key thermal parameters
- This type of testing aims to reduce design deficiency risk
- Typically, non-flight hardware used for test article
  - You must understand your needs for the fidelity of the test article (thermal control model or thermal mock-up)

MER Propellant Line Thermal Blanket Development Test

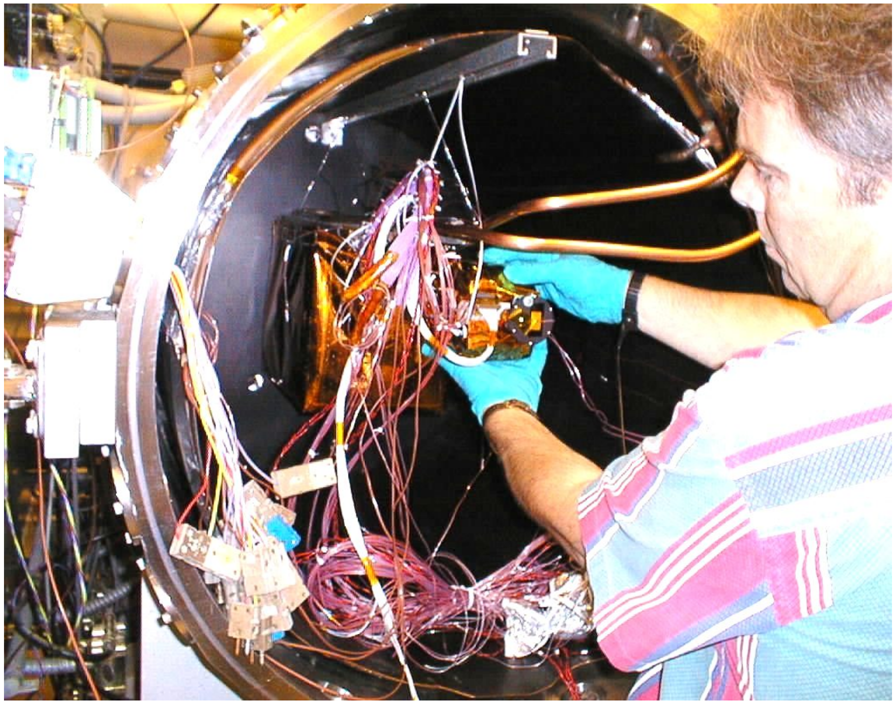
- **Objective**
  - To characterize effective emittance for a series of blanket geometries
    - Straight
    - Tee
    - Elbow



- **Results were imported into analytical model for heater sizing**
  - Thermal balance for a propellant line zone is on the order of a few tenths of Watts

APEX Camera & Electronics Thermal Development Test

- **Objectives**
  - To determine amount of Mars nighttime survival heater power for the camera
  - To determine amount of camera warm-up heater power
  - To determine camera thermal response to transient changes in atmospheric & effective sky temperatures
  - To determine effectiveness of electronics thermal insulation
    - Novel approach that uses stagnant in-situ Mars atmosphere
  - To characterize electronics heat loses through insulation, mounting, and cabling



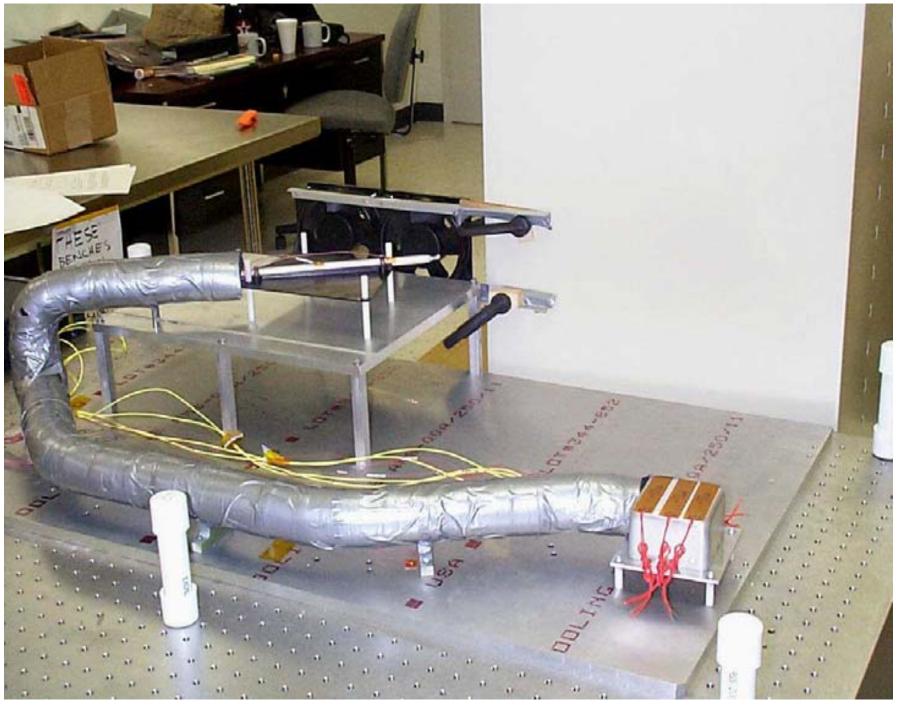
- **Results**
  - Adopted novel insulation approach as baseline
  - Verified survival & warm-up heater camera power
  - Correlated analytical model to transient test data

Assembly Protoflight/Qualification OR Flight Acceptance Testing

- Used to demonstrate assembly workmanship and design reliability
  - Sometimes referred as “margin testing”
- Test temperature levels, dwell times, temperature ramp rates, and number of thermal cycles are dictated by institutional or project policies
- Traditional test program is QUAL/FA or PF
  - EM hardware subjected to QUAL testing
  - FLT hardware subjected to FA testing
  - OR FLT hardware subjected to PF testing

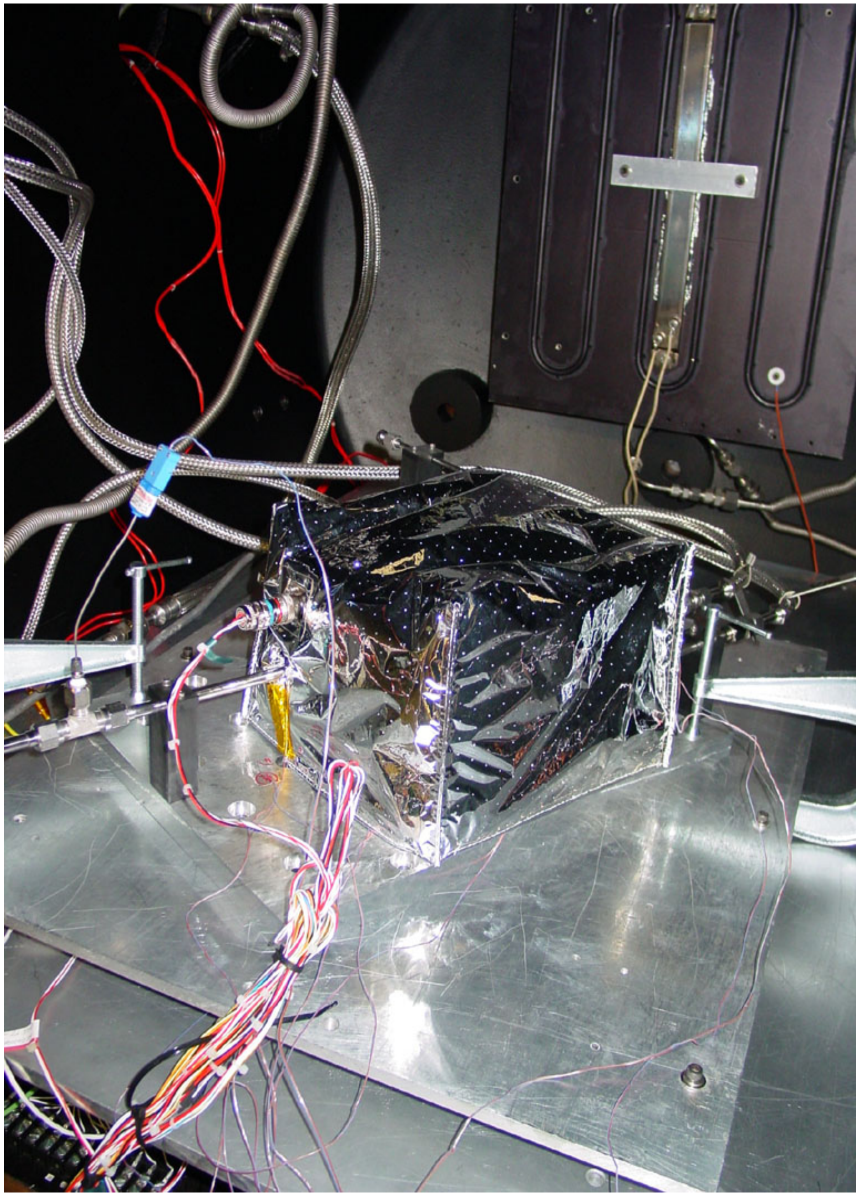
Mars'01 Lander Heat Pipe Flight Acceptance Test

- **Objectives**
  - **Validate flight units function in reflux mode in-air**
  - **Validate capability to transfer 1 watt under various tilt angles**
  -
  - **Quantify thermal gradients along heat pipe**
  - **Compare pre-start-up thermal gradients to analytical predictions**
- **Results demonstrated that flight units would transfer sufficient heat during cruise to Mars**
  - **Hardware accepted for flight**



MER Integrated Pump Assembly Thermal Protoflight Testing

- **Objective**
  - **Demonstrate in-specification performance (pump ΔP & flow rate) over temperature ranges greater than allowable flight temperature (AFT) limits**
  - **Operating AFT limits**
    - **-20ºC to +30ºC**
  - **Operating Protoflight (PF) limits**
    - **-35ºC to +50ºC**
  - **Dwell durations**
    - **Cumulative 24 hours cold**
    - **Cumulative 50 hours hot**
  - **Number of thermal cycles**
    - **3 times lifetime requirement**
    - **3 test cycles**
- **Test results met objectives**
  - **Hardware accepted for flight**



System- OR Assembly-Level Thermal Balance Testing

- **Used for thermal design validation and hardware functionality in expected thermal environment**
  - **“Validation” versus “Verification”**
  - **First discovery of a design deficiency is very costly (budget & schedule) to rectify at this point**
  - **Hardware functionality includes thermal items such as heaters, thermostats, temperature sensors, heat pipes/CPLs, & pumps**

- **Two basic approaches**
  - **Empirical**
    - **Bounding worst-case thermal environments**
  - **Combination of test & analysis**
    - **Specified hot & cold thermal environment to obtain data for analytical model correlation**
    - **Analytical model utilized to demonstrate design requirement compliance**

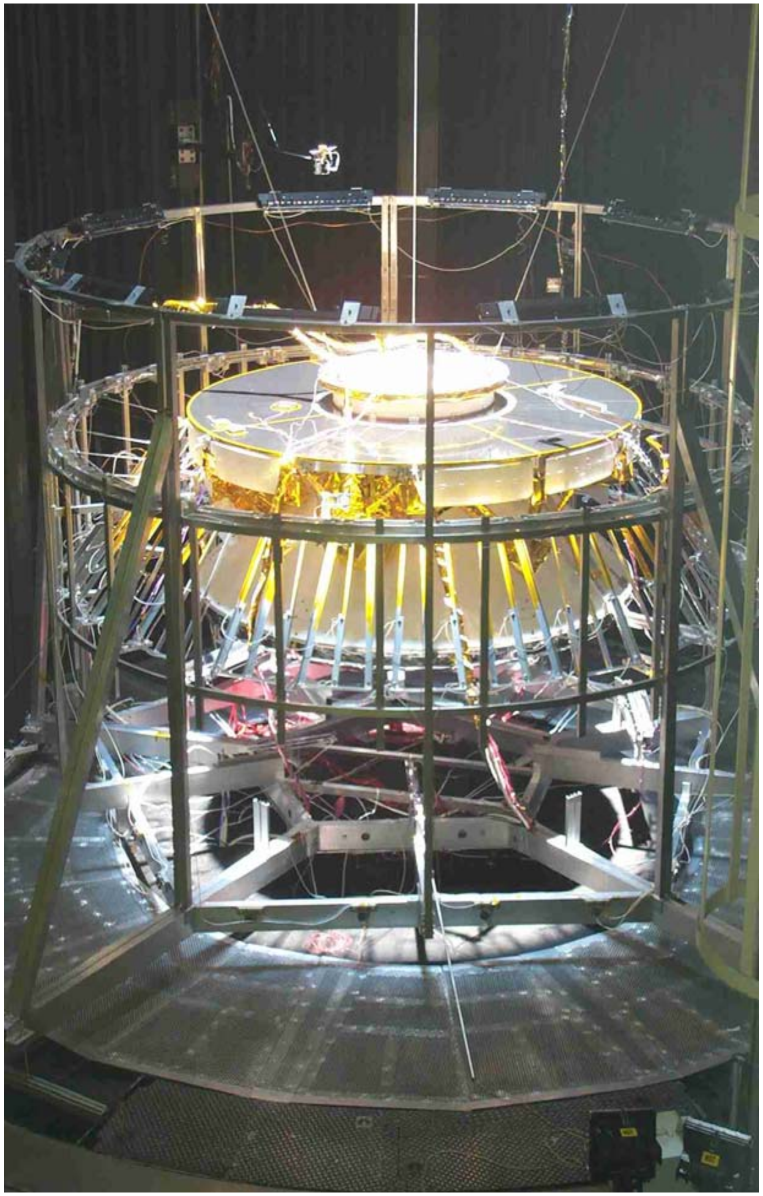
GALEX Instrument Thermal Balance Testing

- **Objectives**
  - **Validate instrument thermal design for worst-hot & -cold Earth orbit conditions**
  - **Validate survival (primary & secondary) heater string operation**
  - **Validate optical performance**

- **Design validation was empirical**
  - **Test results met objectives**
    - **Design maintained allowable flight temperatures for extreme environmental cases**
    - **Primary & secondary survival heater strings validated**

MER Cruise Thermal Balance Testing

- **Objectives**
  - Validate thermal design for mission worst-hot & -cold conditions
    - Solar simulation used
    - IR lamps used for off-sunpoint simulation
  - Validate mechanical pump fluid loop operation
  - Validate primary & secondary thermostatic heater strings
- **Design validation was empirical**
  - Test objectives met
  - Uncovered swapped primary & backup thermostats on four assemblies
  - Determined –Z sun sensor did not require silverized Teflon tape



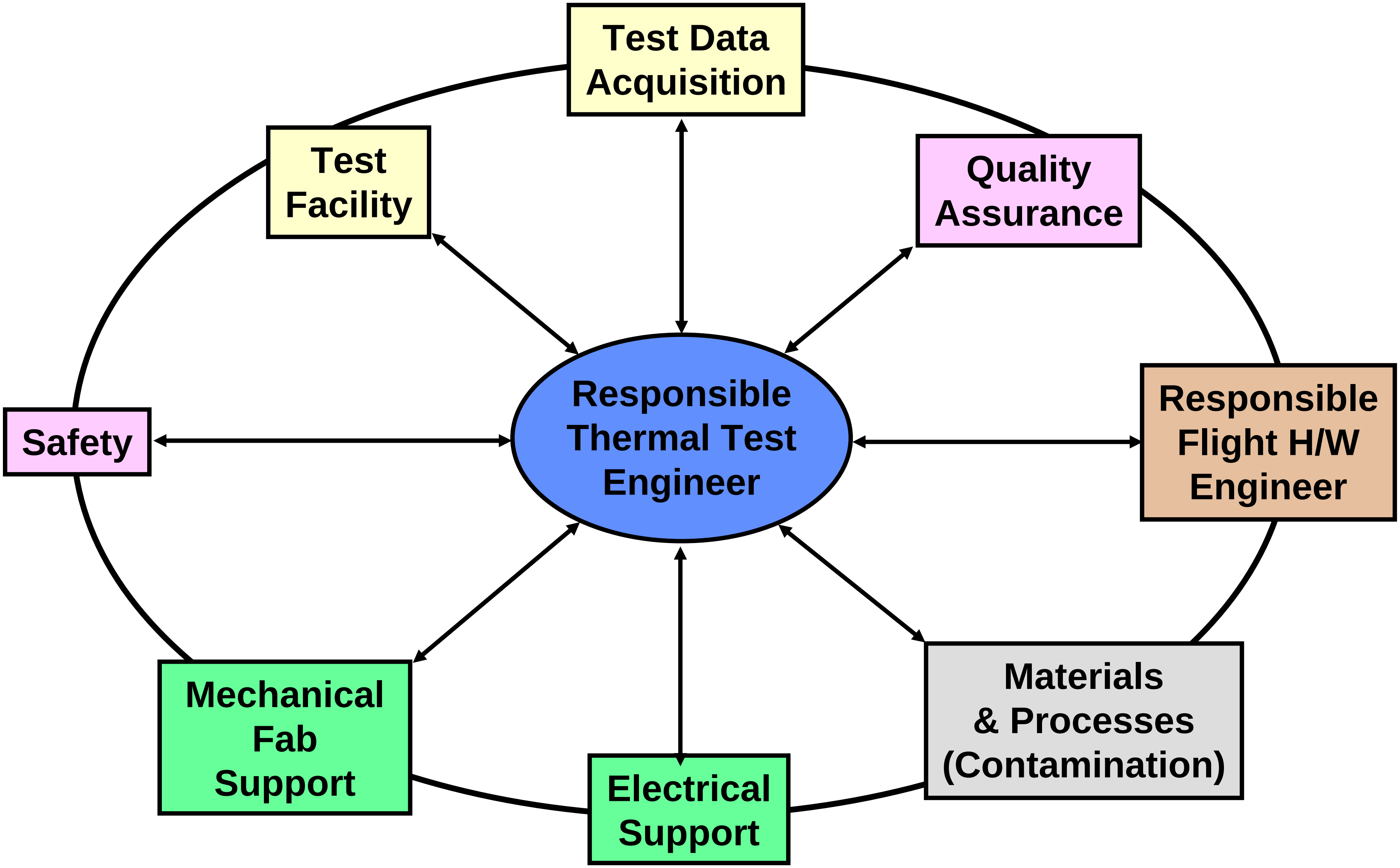
MER Mars Surface Thermal Balance Testing

- **Objectives**
  - **To perform representative steady-state & transient cases to gather empirical data for analytical model correltation**
    - **Simulation of Mars surface environment extremely challenging (e.g., diurnal solar heating, wind simulation, 3/8 gravity field, CO_2 atmosphere)**
  - **To validate critical deployments & releases at cold temperature**
  - **To perform science instrument calibration at various temperatures**
- **Design validation used a combination of test & analyses**

- **Results**
  - **Test data confirmed development test results that WEB thermal design is robust**
  - **Provided empirical data for actuator heater warm-up validation**
  - **Demonstrated critical deployments & science calibrations**

General Planning Issues

The World According to the Thermal Test Engineer



Your Role as Thermal Test Engineer

- Understanding your role as responsible thermal test engineer
  - Clear and decisive communication with your interfaces is critical
    - Be proactive; attend to issues quickly & prevent new ones from arising
  - Develop well-defined and verifiable test objectives
    - This will define how the test will be simulated and instrumented
    - Identify special tests
  - Know your responsibilities for ensuring hardware & personnel safety

- Planning becomes more intertwined with other parties as you move from a thermal development test to an assembly-level qualification/acceptance test to a system-level thermal test

- **Test planning involves a significant amount of your time & effort so allocate ample time in your schedule**

Elements of the Test Plan

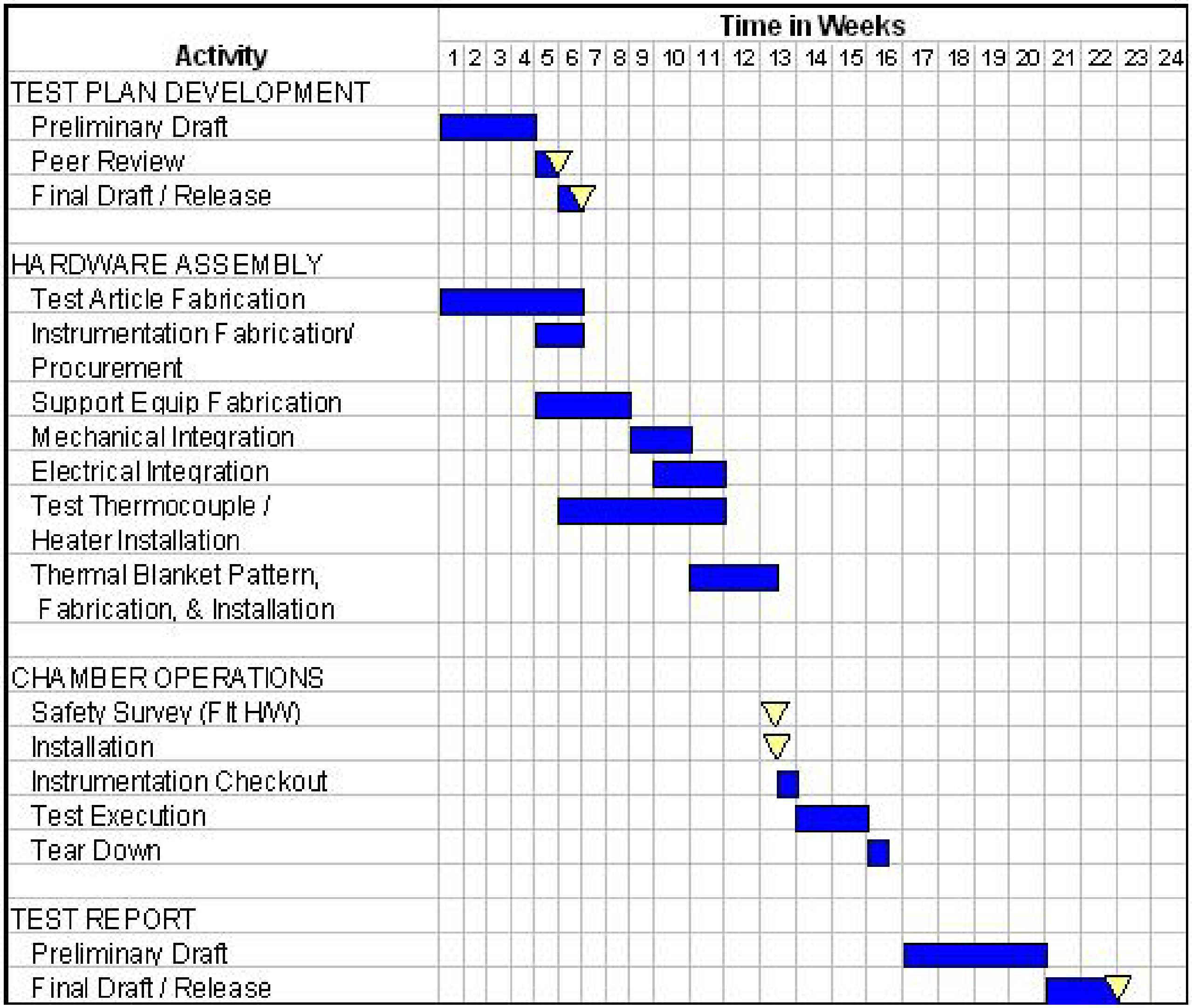
- Objectives
- Test Article
- Test Setup
- Chamber Facility
- Data Acquisition
- Mechanical & Electrical Support Equip
- Test Matrix
- Cost & Schedule

Planning: “Rome Wasn’t Built in a Day” (1/3)

- **Why is a plan needed?**
  - **Tool that initiates & guides the test planning & preparation process**
  - **Acts as the driver to totally engage the responsible thermal test engineer**
    - **Allows you to stay on top of all test aspects, even as the test evolves**
  - **Stimulates feedback from the key interfaces**
    - **Leads to a more efficient use of resources**

Planning: “Rome Wasn’t Built in a Day” (2/3)

- **How long does the planning & preparation process take?**
  - **Schedule shown is typical of development testing**



Planning: "Rome Wasn't Built in a Day" (3/3)

- **High-level schedule for system thermal testing (STT)**

Event	Timing
Preliminary STT Concept	Thermal PDR
STT Preliminary Plan Peer Review	4 Weeks Prior to Thermal CDR
Preliminary STT Plans	Thermal CDR
Preliminary STT Plan Release	2 Weeks Prior to ETRR
Preliminary STT Plan Summary	ETRR
STT Final Plan Peer Review	6 Weeks Prior to STT Start
STT Final Plan Project Review	4 Weeks Prior to STT Start
STT Final Plan Sign-off	2 Weeks Prior to STT Start
STT Preliminary Results Presentation	1 Week After STT End
STT Final Test Report Peer Review	10 Weeks after STT End
STT Final Test Report Release	3 Months After STT End

Objectives: "The Chicken is Involved for Eggs; The Pig is Committed for Bacon"

- **Test objectives are the very core of the test**
  - Specific
  - Verifiable from the test results

- **Objectives fall into two categories**
  - Primary
  - Secondary or Special

- **Primary objectives**
  - Very often, linked to Project Level 3 & 4 requirements
  - "To determine the survival heater power for the worst-case cold Martian surface thermal environment"
  - "To demonstrate in-specification telescope optical performance at the hot and cold flight acceptance temperature levels"
  - "To verify that the temperature control design will maintain the spacecraft and all its elements within allowable flight temperature ranges while operating over the environmental extremes expected for the mission"

Objectives: "The Chicken is Involved for Eggs; The Pig is Committed for Bacon"

- **Secondary or special objectives**
  - **Tests present unique opportunities to obtain additional empirical information to more fully understand the thermal design**
  - **If properly planned, the gathering of this information will be of minimal impact to the primary test flow**
  - **Examples**
    - **Sensitivity of temperature to power**
      - Optimize size of flight heaters
      - Assess effect of poorly-known or degraded thermal properties
      - Assess heater element failure
    - **Sensitivity of temperature to boundary conditions**
    - **Determine temperature changes after switching from primary to redundant equipment**
    - **Obtain information for mission operations**
      - How long can heaters (or equipment) be turned off?
      - How long does it take a heater to do its warm-up job?

Objectives: "The Chicken is Involved for Eggs; The Pig is Committed for Bacon"

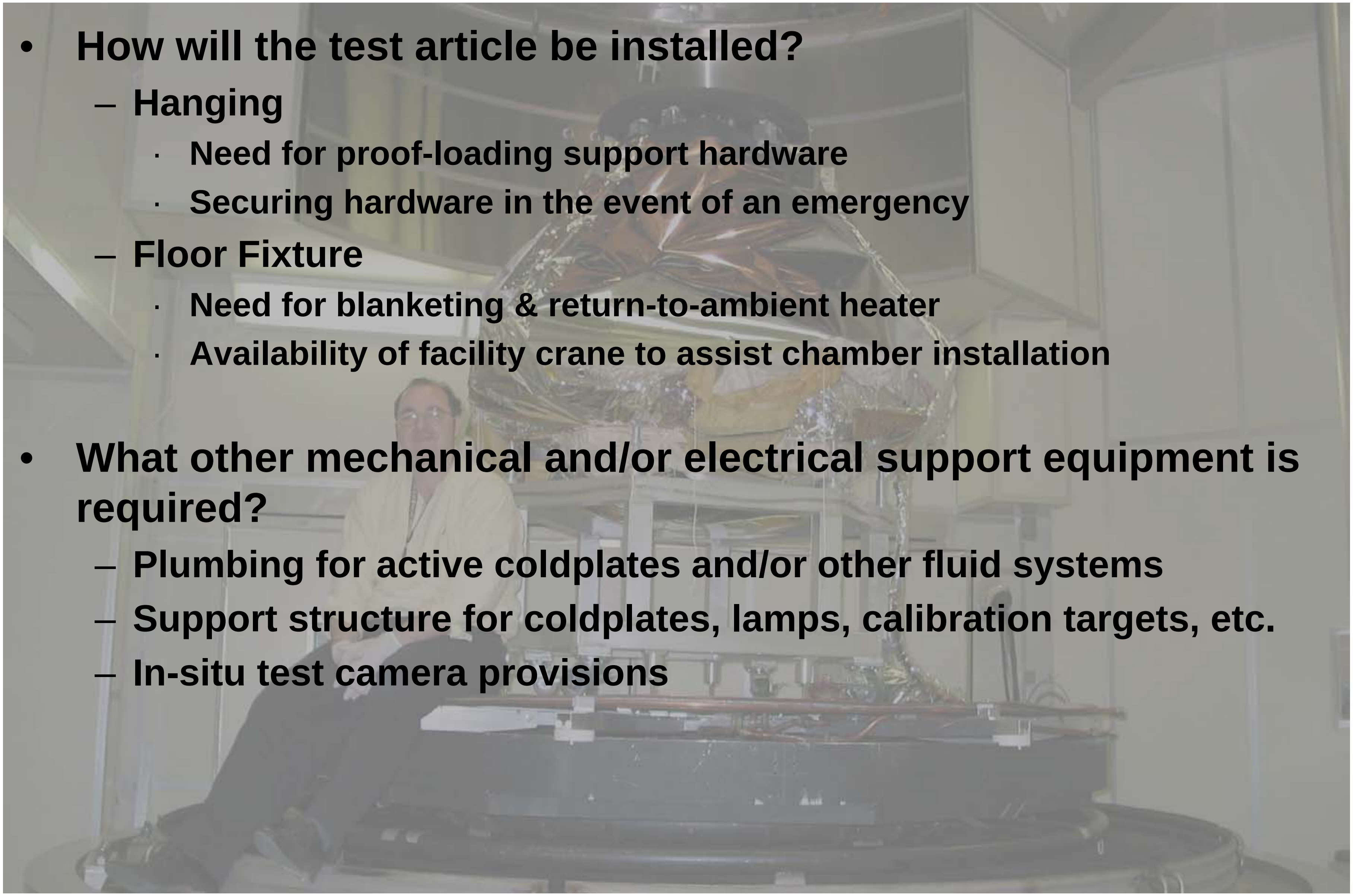
- **"Permissible" temperature limits when using flight hardware**
  - **Although there are established Level 3 allowable flight temperature limits, there is no universally accepted interpretation of permissible limits during test**
  - **Permissible test limits are the criteria for the generation of problem reporting documentation**
    - **A balance between hardware safety & test flexibility must be struck**
    - **Flight hardware should be only exposed to temperature levels within previous environmental test experience**
    - **At JPL, flight acceptable (FA) test limits have constituted permissible test limits**
      - Enabled testing to continue when marginal allowable flight temperature violations occurred

– You must unambiguously define these limits & reach agreement with the appropriate parties <u>before the test begins</u>

Test Article: What Is It That We're Testing?

- **Developmental testing usually uses non-flight hardware**
  - You must define the key thermal requirements for the fabrication of the test article
    - How important is fit & form?
    - How important is the article mass?
    - How will internal power be simulated?
    - Replication of heat transfer paths including radiation (i.e., surface finish)
    - Egress of test heater & temperature sensor cabling
    - Avoid cadmium-plated fasteners (not vacuum qualified)
  - Use of flight hardware will complicate the test planning
- **Protoflight/Qualification & Flight Acceptance testing involves flight hardware**
- **System-level testing involves primarily flight hardware**
  - However, EM or QUAL units may be used as substitutes when flight hardware is late
  - You will need to assess the impact to your objectives if such substitutions occur

Test Set-up Considerations



- How will the test article be installed?
  - Hanging
    - Need for proof-loading support hardware
    - Securing hardware in the event of an emergency
  - Floor Fixture
    - Need for blanketing & return-to-ambient heater
    - Availability of facility crane to assist chamber installation
- What other mechanical and/or electrical support equipment is required?
  - Plumbing for active coldplates and/or other fluid systems
  - Support structure for coldplates, lamps, calibration targets, etc.
  - In-situ test camera provisions

Test Facilities Considerations

- **Ensure that the facility has been certified for the environmental testing that you will conduct**
  - Facility safety survey
  - Cleanliness
- **Select minimally-sized chamber subject to:**
  - Test objectives
  - Critical mechanical clearances to chamber wall
  - Accommodation of other support hardware
- **Most thermal tests require a cold shroud**
  - Understand temperature ranges & stability
  - Understand impact of close proximity of the test article to shroud
  - Do you also require a door shroud?
- **Optical test articles may require a chamber window**
  - Special thermal considerations to reduce impact of window
    - Reduce aperture area with thermal blanketing or highly reflective shield
    - Use a long-length chamber & place test article as far from the window as possible
- **Ensure that the surrounding external chamber area is sufficient for staging and accommodation any GSE**

Test Data Acquisition Planning (1/2)

- **How do you determine where the thermocouples & test heaters are located?**
  - **Temperature data that will directly lead to verifying your objectives**
  - **Temperature data that will provide a better understanding of your design**
  - **Temperature data that will not be measured in-flight**
  - **What hardware requires safeguarding in event of a facility failure or test problem?**
  - **Consider supplementing flight heaters where practical**
    - **Accelerate achievement of steady-state**
    - **Accelerate transition to return-to-ambient**
  - **Consider *in-situ* massive support equipment which need warm-up acceleration upon return-to-ambient**

- **Defining computed data from raw test data**
  - **Maximum, minimum, & average temperatures**
  - **Spatial temperature difference**
  - **Temperature rate of change**
  - **Internal power dissipation**

Test Data Acquisition Planning (2/2)

- **Defining how you want the data sampled and displayed**
  - What data should be grouped together for display?
  - Define display lists & plots for implementation
  - Formulate yellow & red alarm temperature limits

- **Power supply capabilities**
  - Define quantity & capability
    - Voltage or current range
    - Define maximum voltage and/or current limits
  - Availability of proportional heater controllers
  - Replication of thermostatic heater control

Mechanical & Electrical Support Equipment

- **Development testing will require a significant amount of mechanical fabrication support**
  - **Get them involved with the planning process as early as possible**
    - **Seek feedback about feasibility of thermal mock-up design & fabrication**
      - Includes support hardware & thermal blanketing

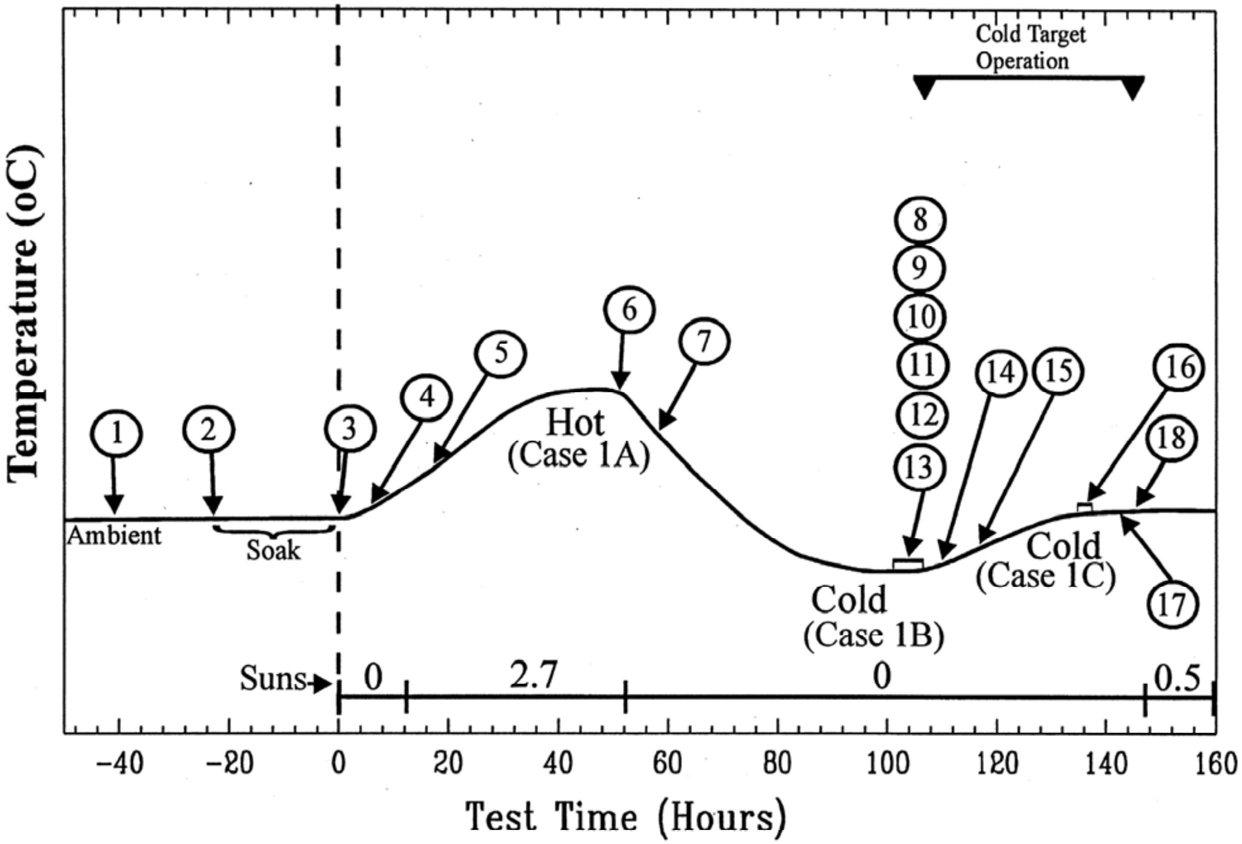
- **PF/QUAL/FA & system-level testing will require flight technicians to assemble and integrate flight hardware for the test**
  - **Get involved to understand the mechanical & electrical integration flow**
  - **Identify the need for the fabrication of support hardware**
    - **Develop a mutually acceptable schedule**
  - **Identify key times where test instrumentation & blanketing can be installed**

Test Matrix Development Process (1/2)

- The challenge: Determine how best to incorporate all of the test objectives within an allocated test time period
  - The resolution process involves the stakeholders of each test objective
  - This process becomes more complex when a system-level thermal test is involved
- The process
  - Identify major test divisions on a timeline
  - Identify when specific events occur
  - Focus on first accommodating primary objectives & then finding non-intrusive time periods (from a thermal perspective) for special tests & objectives
- Ideally, use analysis to assist test case & transition durations
  - The "design" analytical model must be transformed into a "test" analytical model
  - This is a significant effort that you must include in your planning

Test Matrix Development Process (2/2)

Cassini STV Test Phase 1 Event Timeline



Event No.	Description
1	S/C Baseline Test
2	Close Chamber
3	Nitrogen Flush Start Cooling Shrouds
4	Turn OFF Purge
5	Configure Power for Case 1A
6	Turn off Heaters TBD for Cooldown Acceleration
7	Configure Power for Case 1B
8	CIRS Interference Test
9	CAPS HV Test
10	CDA Interference Test
11	ISS Interference Test
12	Radar 30 minute Turn-ON
13	RWA 30 minute Turn-ON
14	Turn on Heaters for warm-up acceleration
15	Configure Power for Case 1C
16	CIRS, VIMS & ISS Functional Tests and CIRS Microphonics Test
17	Configure Power for Backfill
18	turn ON Purge

Reviewing Your Test Plan

← Prior to Test → Test Execution ← After the Test →

Prior to Test

- Test Plan Peer Review
- Environmental Test Readiness Review
- Operational Safety Survey

After the Test

- Test Results Review
- Post-Test Review

Blue font indicates required when flight hardware present

Test Execution Considerations

- **Effective use of available workforce**
  - Use your discretion to determine if a test must be run around-the-clock
  - Identify primary & relief monitoring workforce
    - Identify test shift lead & communicate this information to the Facility & Integration/Test personnel
    - Ideally, limit each engineer to 1 shift for no longer than 5 consecutive days, followed by 2 non-working days
  - Critical events may warrant increased staffing

- **Criteria for attainment of steady-state**
  - Criteria should be <u>used only as a guide</u>
    - JPL has considered <0.3ºC per hour for 3 consecutive hours
  - The responsible thermal test engineer shall use his/her discretion to determine when thermal equilibrium has been sufficiently approached

- **Develop a prioritized emergency contact list & post at monitoring workstation**

Communication Ensures Good Test Coordination

- **As the responsible thermal test engineer, you must ensure that the test is performed within budget & schedule**
  - **Confirm that test stakeholders are aware of & buy-in to your approaches & methods**
  - **When multiple interfaces are involved, you should initiate regular meetings to stay on top of & help resolve any issues**

- **Communicate regularly with mechanical and/or electrical fabrication personnel, especially during the fabrication process**

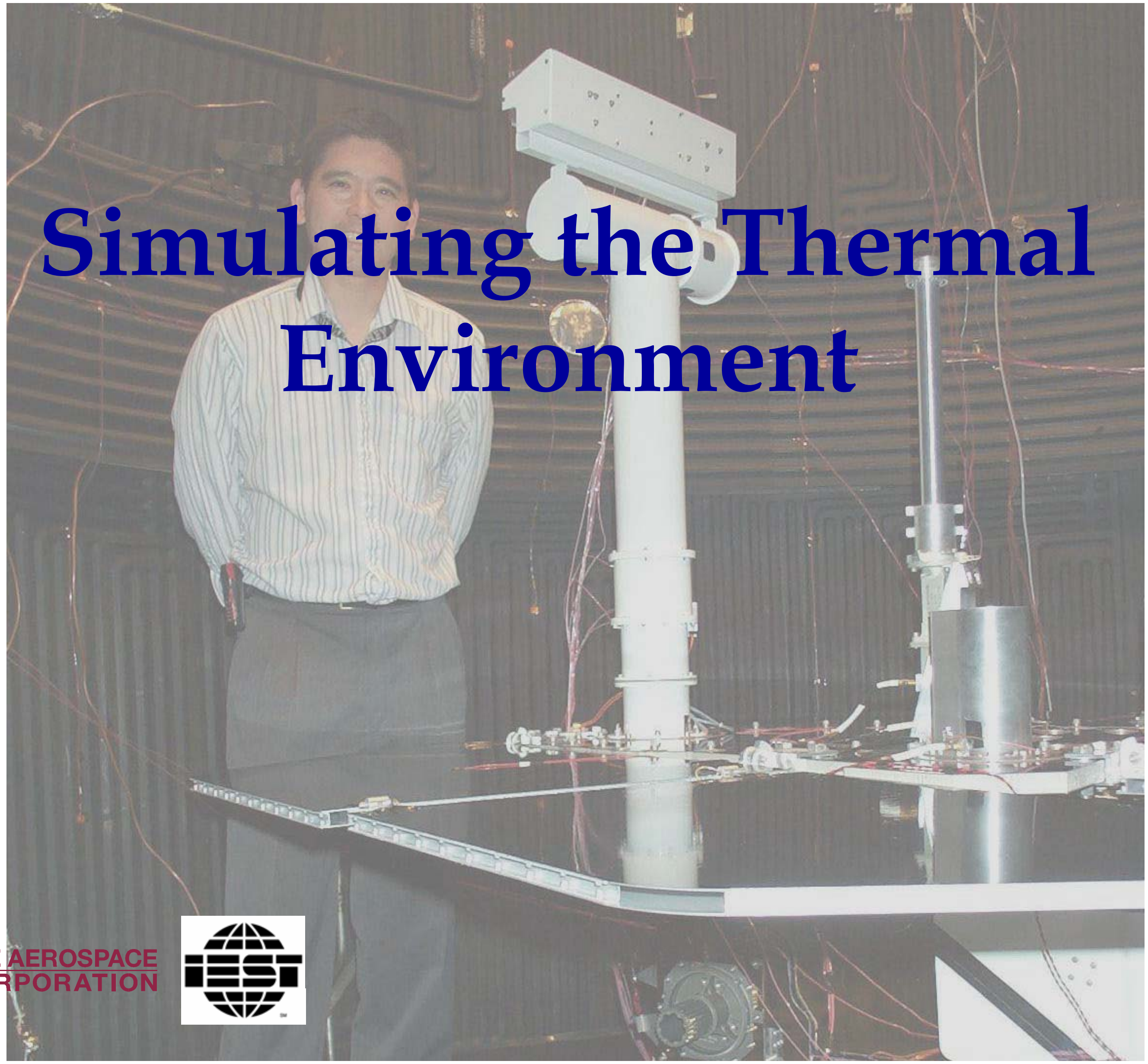
- **Maintain a presence in the Integration & Test arena since this activity is "fast & furious"**
  - **Decisions are sometimes made informally & quickly**
  - **"Out of sight; out of mind"**
  - **A dedicated thermal engineer for this purpose is ideal**

Be Proactive: Contingency Planning

- Consider design weaknesses that may be uncovered as deficient
  - Develop a list of problems that may be encountered & how you would respond to them
  - With & without breaking chamber, what additional testing could be performed?
    - Provide schedule margin to recover from a design deficiency
  - Could some design feature be included in the test setup to provide flexibility?
    - Provide more required radiator area or heater power
  - Identify “gotta have” test cases versus “wanna have” test cases
    - Recovery from a deficiency may result in deletion of test cases to meet Project schedule

- Consider the opposite where the test goes faster than expected
  - What additional testing would provide high value?

Simulating the Thermal Environment



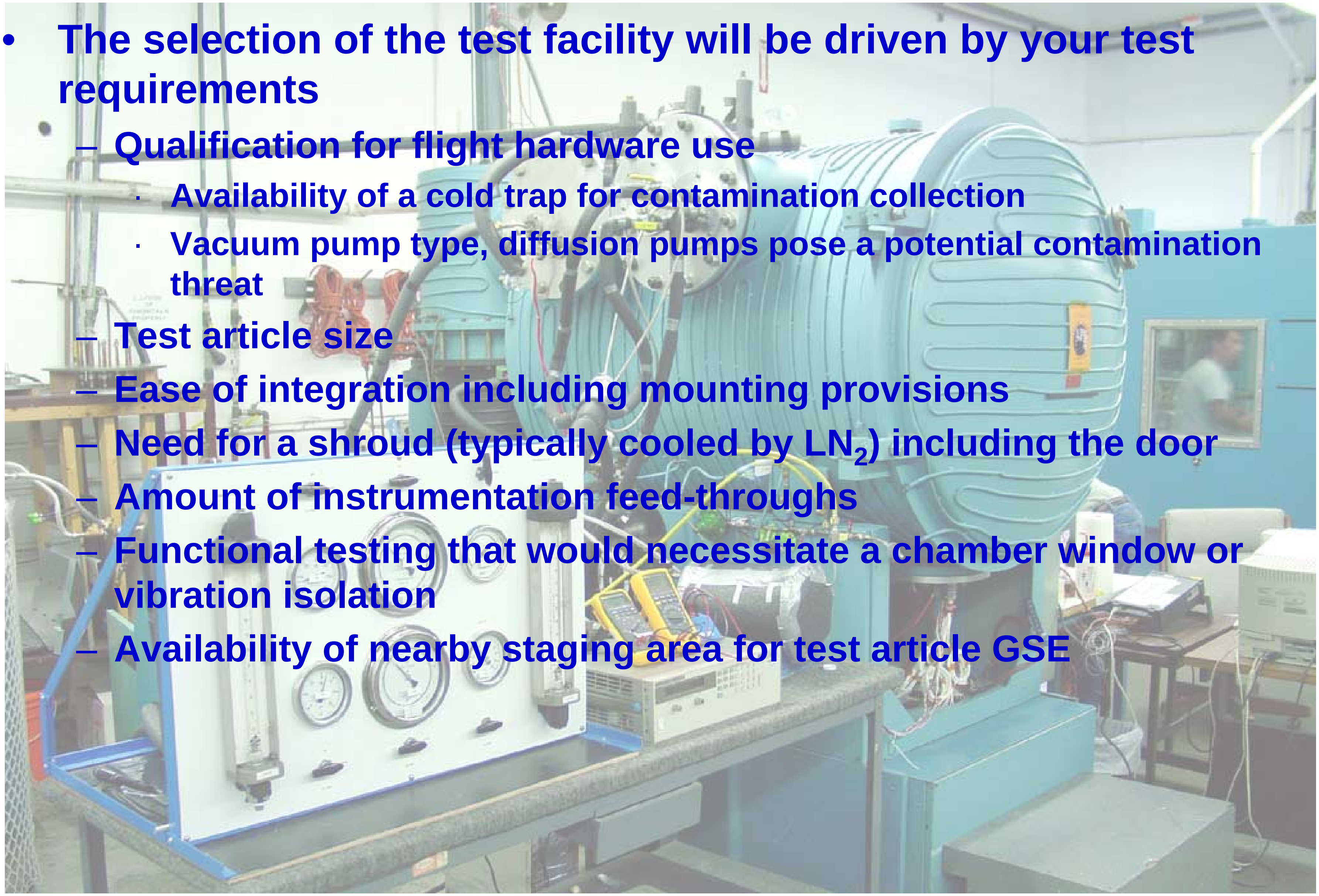
Considerations for Simulating the Thermal Environment

- Your goal should be focused on the pure simulation of the expected environment
  - For thermal balance testing, the test would provide an empirical validation of the thermal design
  - In the case of acceptance and/or qualification testing, your focus should be meeting the specified temperature level (& possibly, spatial uniformity) without exception
- This may be impractical due to several reasons for thermal balance testing
  - Complex time-varying environment
  - Facility limitations
- When pure simulation is impractical for thermal balance testing, knowledge of the simulated environment becomes as important as how the environment is simulated
  - You will be reliant upon an analytical model for design validation
  - The test data will be used to adjust the analytical model

List of Environmental Simulation Tools

- Environmental Chambers
- Environmental Chamber Shrouds
- Conductive & Radiative Boundary Conditions
  - Cold Plates & Cold Targets
  - Heater Plates
  - Achieving Stable Temperature Control
- Test Heaters
- Solar Simulators (Xenon lamps)
- IR Quartz Lamps
- Dewars (Cryogens)

Environmental Chambers

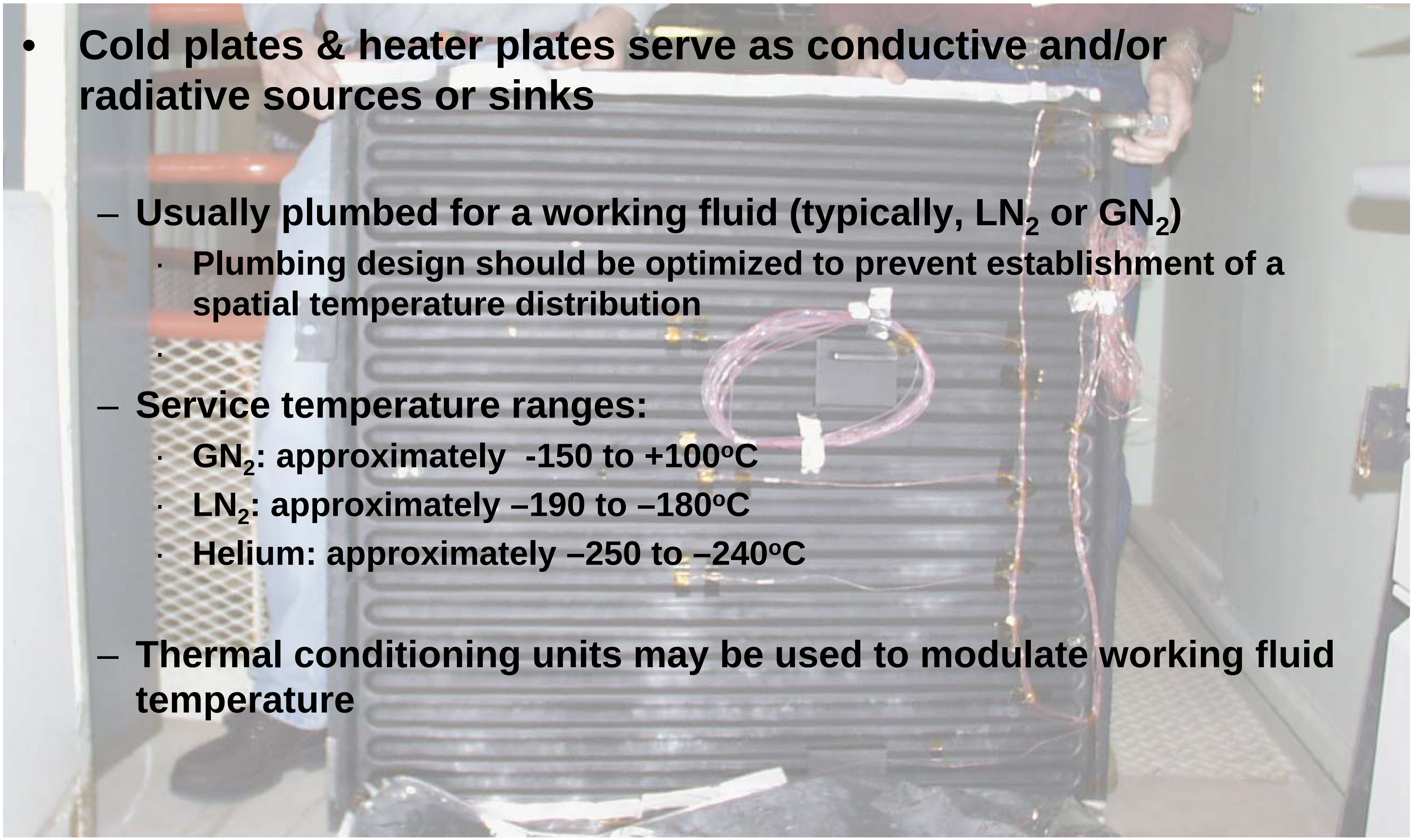


- The selection of the test facility will be driven by your test requirements
  - Qualification for flight hardware use
    - Availability of a cold trap for contamination collection
    - Vacuum pump type, diffusion pumps pose a potential contamination threat
  - Test article size
  - Ease of integration including mounting provisions
  - Need for a shroud (typically cooled by LN_2) including the door
  - Amount of instrumentation feed-throughs
  - Functional testing that would necessitate a chamber window or vibration isolation
  - Availability of nearby staging area for test article GSE

Environmental Chamber Shrouds

- **Typically, shrouds are used to replicate a radiative boundary condition**
  - **For thermal balance test, shrouds usually represent deep space**
  - **Use of shrouds is usually optional for acceptance and/or qualification testing since flight environment simulation is not performed**
  - **Understand the control range of shroud temperature capability**
    - **Flooded with liquid nitrogen, (LN_2 approximately -190 to -170^o C)**
    - **Controlled with gaseous nitrogen (GN_2 approx. -100 to +100^o C)**
- **Strive to understand how the shroud may interact with the rest of your test setup**
  - **Solar simulator reflections**
  - **If shrouds are cooled to cryogenic temperatures, how does the shroud emittance decrease from its room temperature value?**
- **Large chambers require multiple shrouds**
  - **Temperature uniformity requirements may lead you to more instrumentation and/or to understand the shroud plumbing schematic**

Conductive & Radiative Boundary Conditions (1/2)



- **Cold plates & heater plates serve as conductive and/or radiative sources or sinks**
  - **Usually plumbed for a working fluid (typically, LN_2 or GN_2)**
    - **Plumbing design should be optimized to prevent establishment of a spatial temperature distribution**
  - **Service temperature ranges:**
    - **GN_2: approximately -150 to +100°C**
    - **LN_2: approximately –190 to –180°C**
    - **Helium: approximately –250 to –240°C**
  - **Thermal conditioning units may be used to modulate working fluid temperature**

Conductive & Radiative Boundary Conditions (2/2)

- **Cold targets are special cold plates that act as radiative sinks for radiators or sensing apertures**
  - **Black, open-faced honeycomb may be used to increase effecitve emittance**

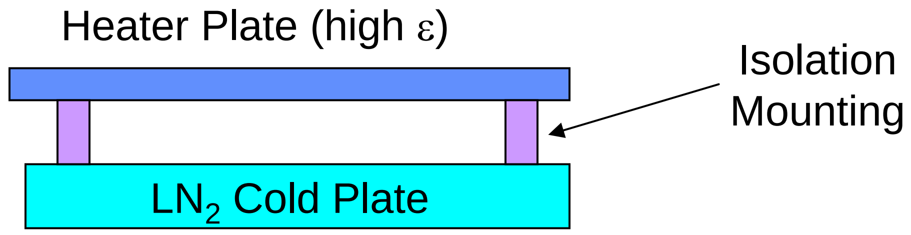
- **Heater plates are usually made from high thermal conductivity material to provide a uniform temperature**

- **Motor-driven louvers can be employed to modulate IR heat flux to or from a cold plate or heater plate**

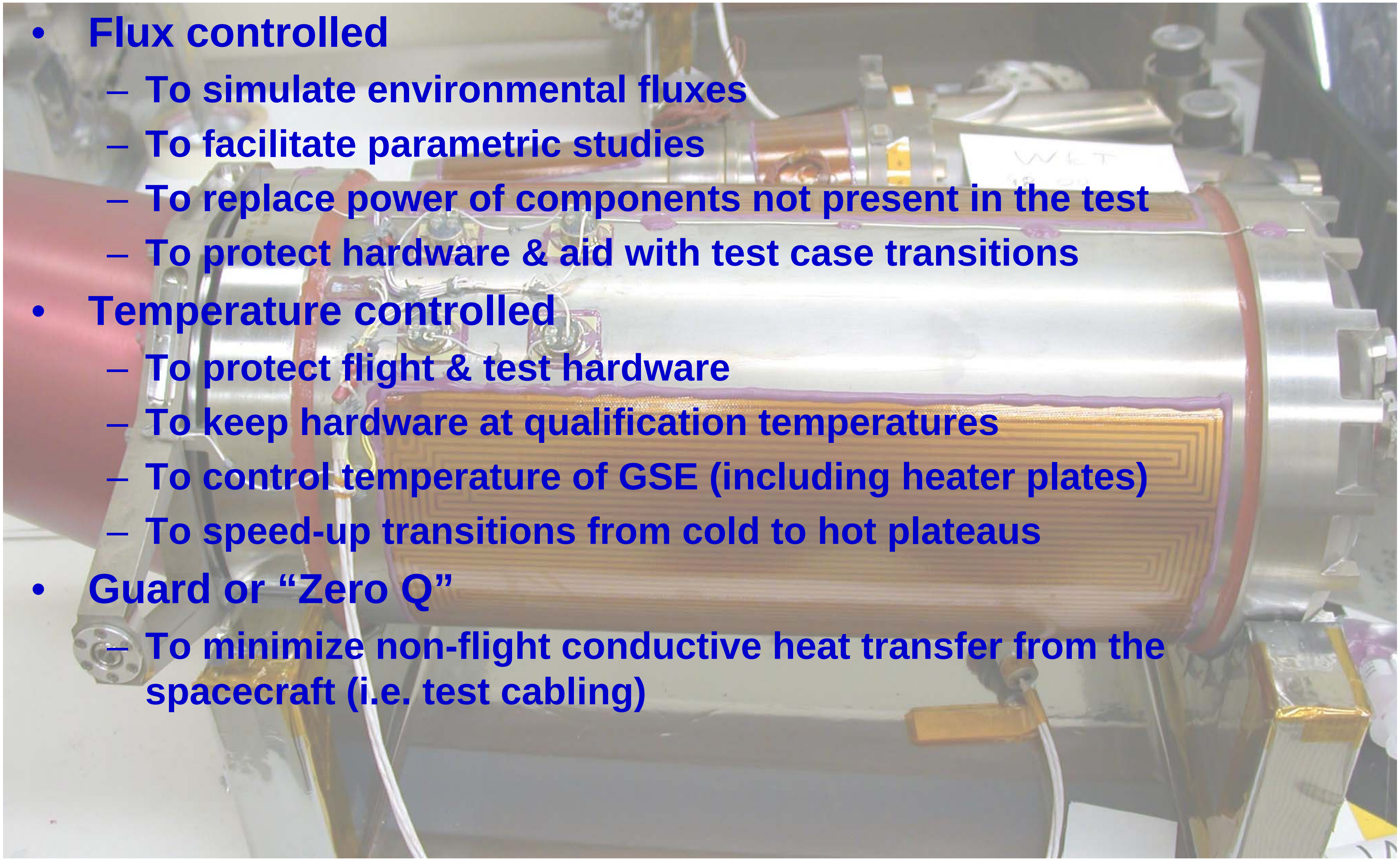
- **Black (high emittance) finish usually preferred**

Archiving Stable Temperature Control

- **Stable boundary temperatures are difficult to attain with a flowing working fluid when goal temperature is significantly greater than phase transition temperature of the working fluid**
  - **Control system becomes a "stiff" situation (i.e., highly sensitive to change in temperature) for the thermal conditioning unit**
  - **This situation can be avoided with a slight design modification**
    - **Control cold plate near phase transition temperature OR more stable goal temperature**
    - **Mount a heater plate with appropriate conductive isolation**
    - **Apply sufficient heater power to meet goal temperature**



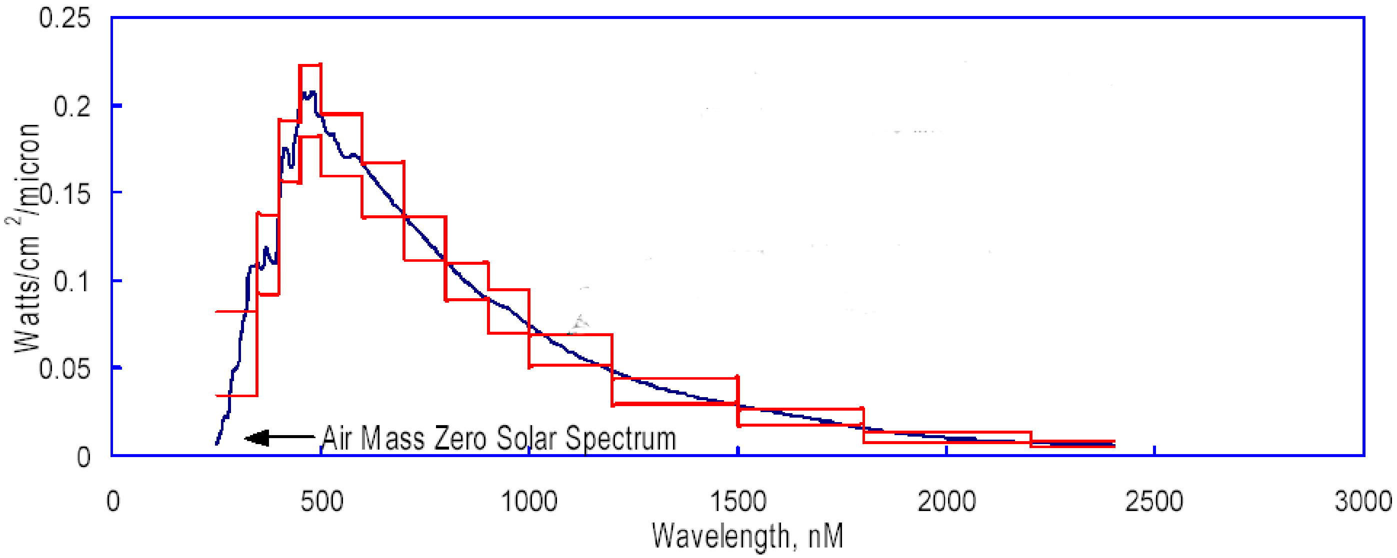
Test Heaters



- **Flux controlled**
  - **To simulate environmental fluxes**
  - **To facilitate parametric studies**
  - **To replace power of components not present in the test**
  - **To protect hardware & aid with test case transitions**
- **Temperature controlled**
  - **To protect flight & test hardware**
  - **To keep hardware at qualification temperatures**
  - **To control temperature of GSE (including heater plates)**
  - **To speed-up transitions from cold to hot plateaus**
- **Guard or “Zero Q”**
  - **To minimize non-flight conductive heat transfer from the spacecraft (i.e. test cabling)**

Solar Simulators (1/2)

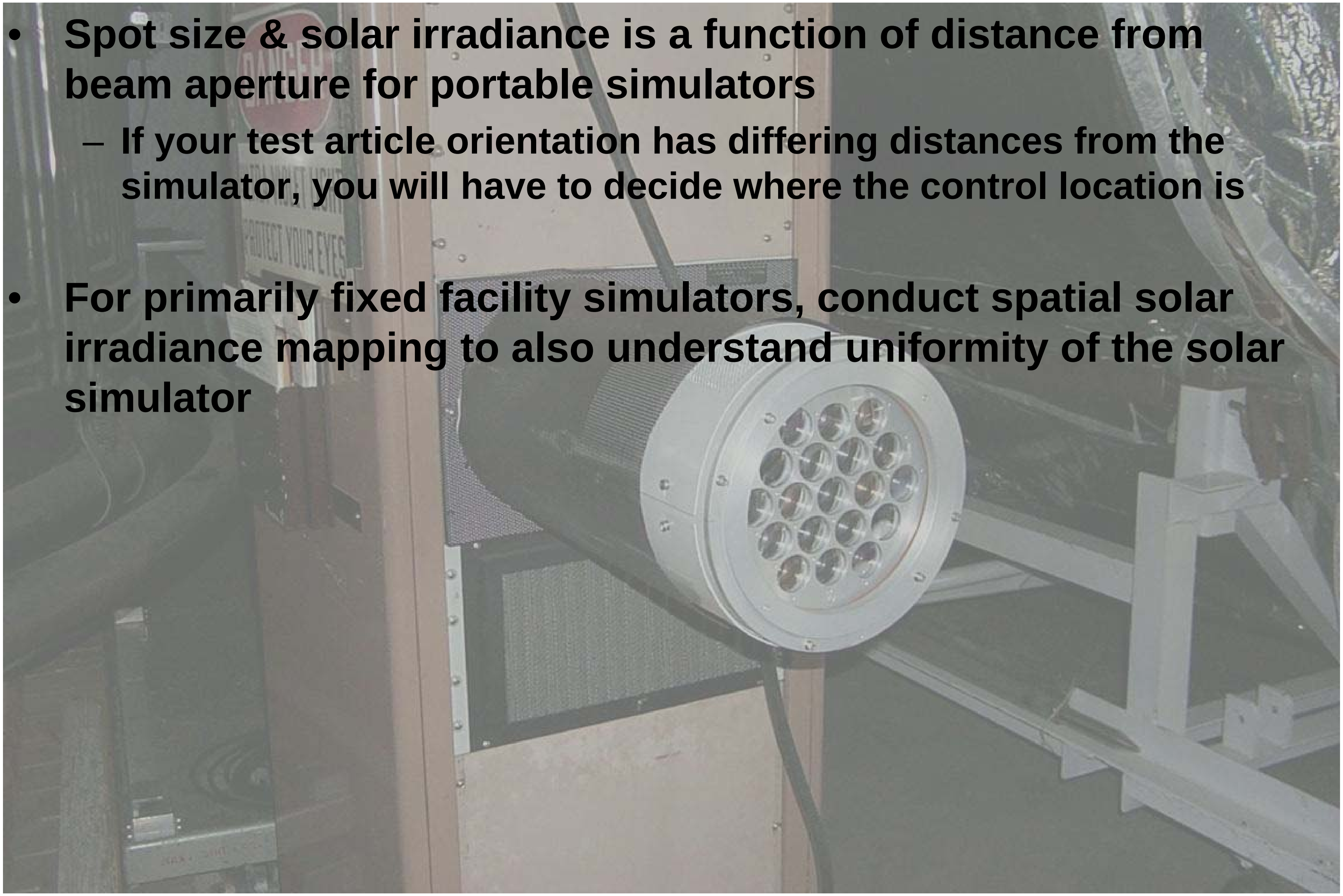
- **Solar simulation is essential for complex geometries where multiple reflections and/or trapping is evident**
- **Two primary Xenon arc lamp types : portable & large fixed facility**
- **Solar simulators approximate the spectral distribution of solar radiation**
  - **Understand how well the spectral distribution is represented**
  - **Thermal control surfaces such as white paints may absorb a different amount of heating than flight**



Solar Simulators (2/2)

- **Spot size & solar irradiance is a function of distance from beam aperture for portable simulators**
  - **If your test article orientation has differing distances from the simulator, you will have to decide where the control location is**

- **For primarily fixed facility simulators, conduct spatial solar irradiance mapping to also understand uniformity of the solar simulator**



IR Quartz Lamps

- **IR quartz lamps provide additional flexibility for environmental flux simulation**
  - **Fixtures can be fabricated to provide appropriate directionality including spin-stabilization environments**
    - **Strive for flux uniformity with appropriate lamp spacing**
  - **Judicious use of calorimeters will enable certain quantification of the absorbed heat flux**
    - **Set aside appropriate budget & schedule to identify, fabricate, & calibrate calorimeters**
  - **Lamps are usually grouped into control zones**
    - **May be limited by number of controllers (electronics)**
    - **Give yourself enough flexibility to provide margin beyond expected simulated environment**
  - **Allocate resources to conduct spatial flux mapping**
- **Although there is a small UV flux component, IR lamps lack the ability to replicate solar trapping**

Dewars (Cryogens)

- Cooling available over temperature range 0.3 - 80 K (with gaps)

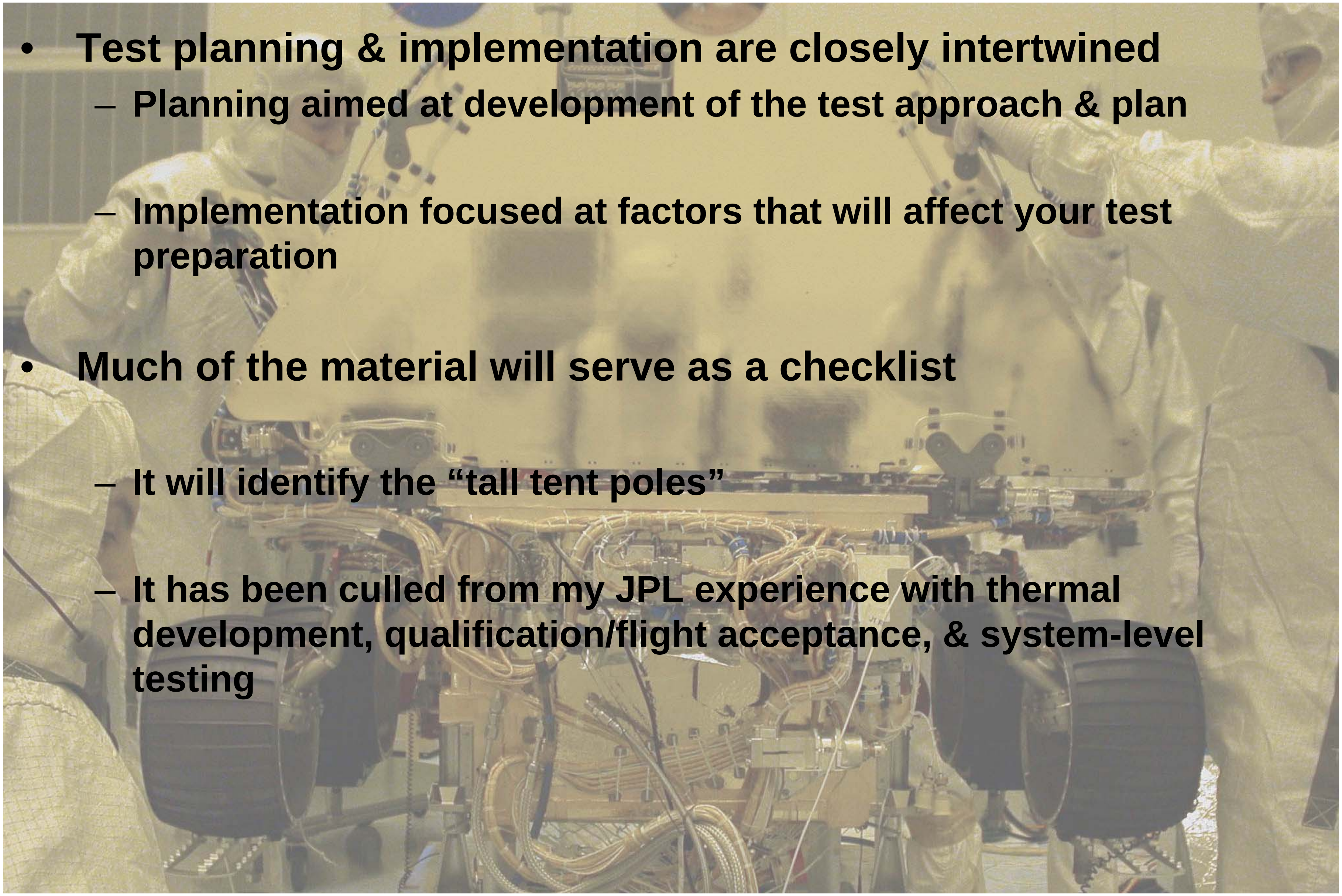
- Solid cryogens
  – Argon (triple point temperature = 83.8 K)
  – Nitrogen (triple point temperature = 63.2 K)
  – Neon (triple point temperature = 24.4 K)
  – Hydrogen (triple point temperature = 14.0 K)

- Liquid cryogens
  – ^{4}He (lambda point temperature = 2.17 K)
  – ^{3}He (0.34 K--record for lowest on-orbit temperature)

- Gravity effects on cryogen

Test Implementation

Introduction



- **Test planning & implementation are closely intertwined**
  - **Planning aimed at development of the test approach & plan**
  - **Implementation focused at factors that will affect your test preparation**
- **Much of the material will serve as a checklist**
  - **It will identify the “tall tent poles”**
  - **It has been culled from my JPL experience with thermal development, qualification/flight acceptance, & system-level testing**

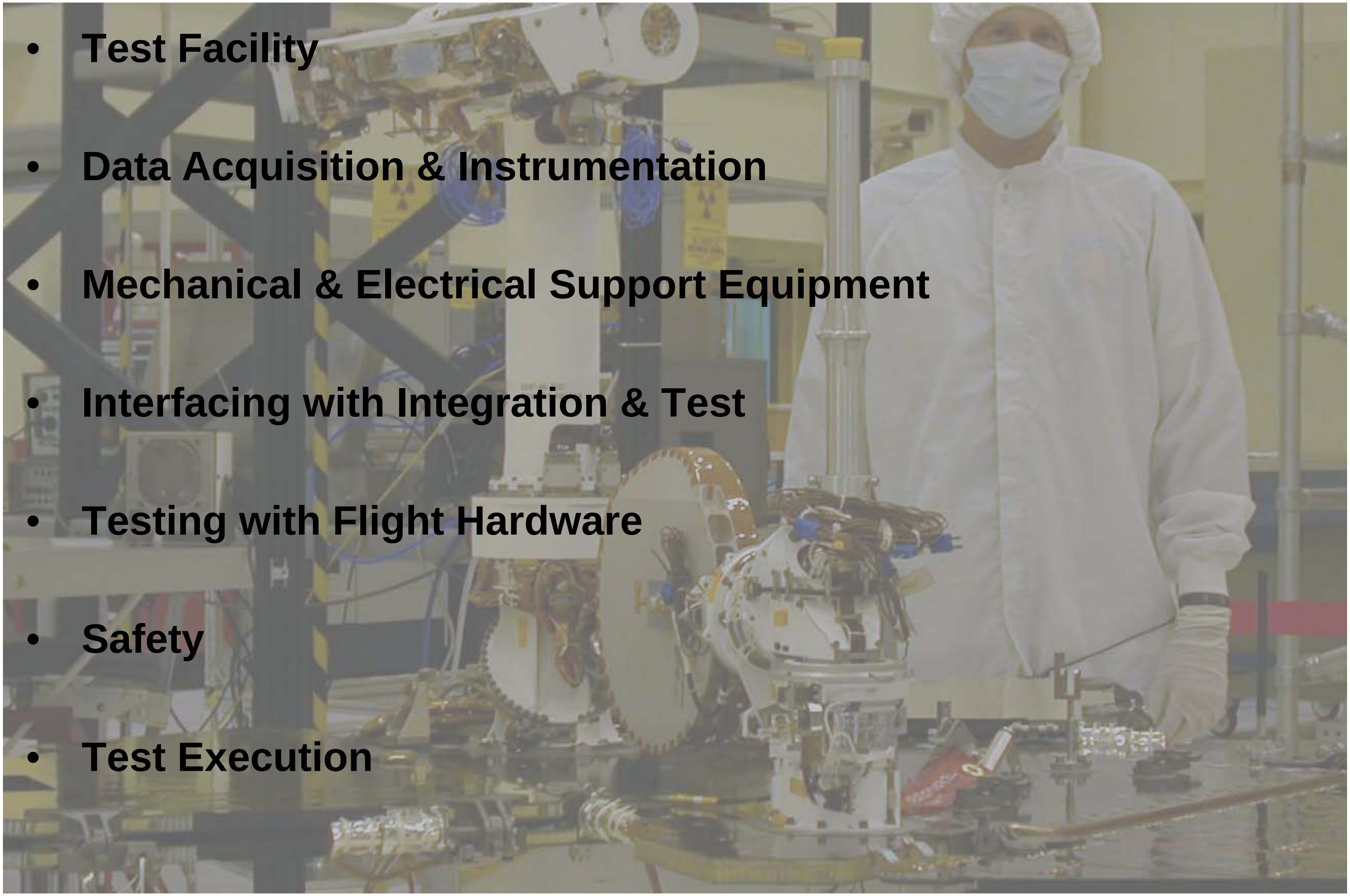
"Sharpen Your Saw"

- You are responsible for overseeing a multitude of tasks & issues covering a wide spectrum of interfaces
  - A process for proactively addressing & attending to each task is essential
    - Prioritized task list that is reviewed daily
    - War charts
    - Daily logbook

- You should know the working style of your team & interfaces
  - Leverage on strengths
  - What is their preferred method of communication?
  - Avoid springing "surprises"
  - Who requires more of your attention & who can be given a "long leash?"

- You should be familiar your institutional and/or project procedures for conducting tests

Prioritized Focus Areas



- **Test Facility**
- **Data Acquisition & Instrumentation**
- **Mechanical & Electrical Support Equipment**
- **Interfacing with Integration & Test**
- **Testing with Flight Hardware**
- **Safety**
- **Test Execution**

Where Should You Test?

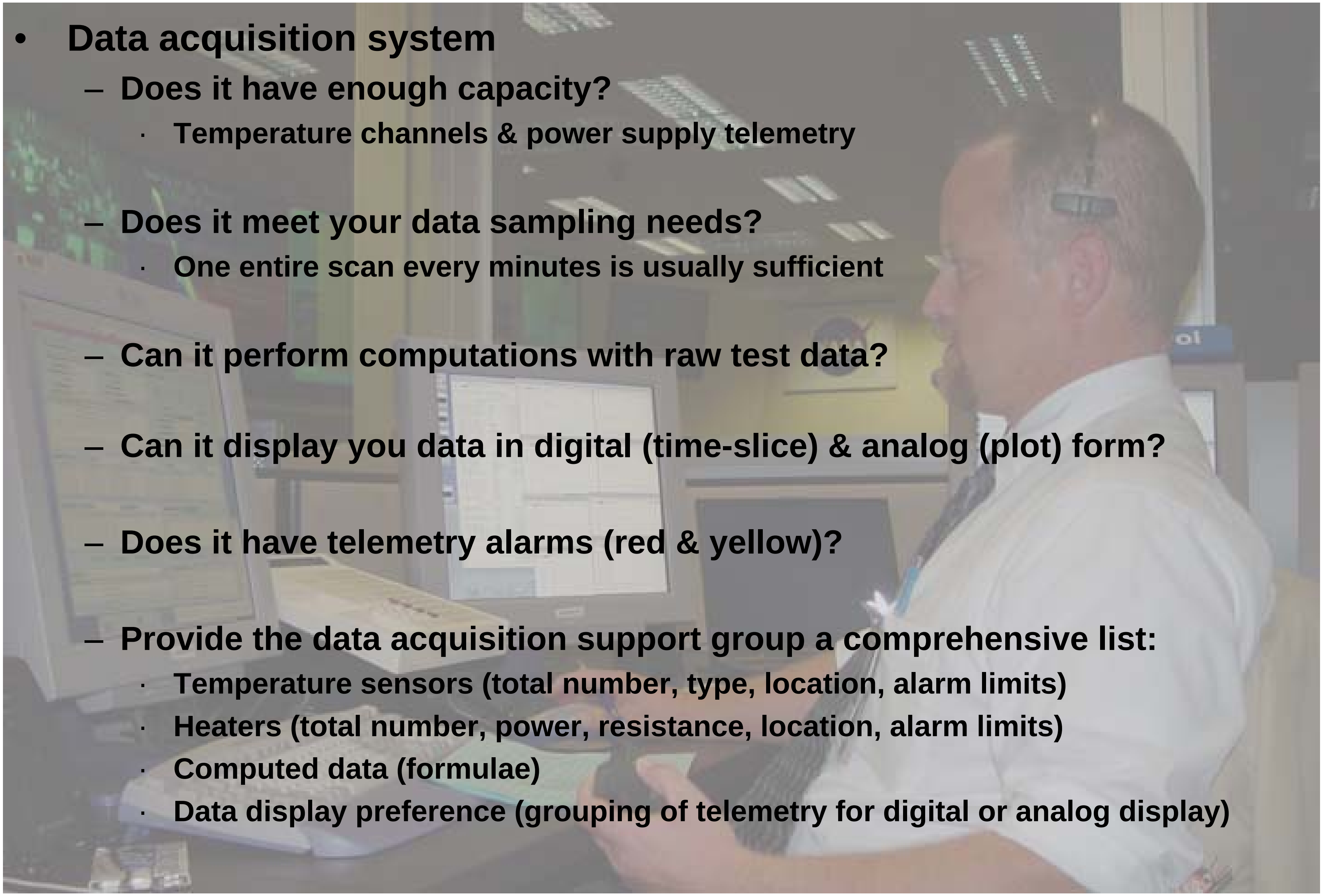
In-house or Out-of-house?

- Appropriate chamber available in-house?
- Can you live with in-house chamber capability?
- What are the transportation risk to your hardware?
- Will your test use a lot of support equipment?
- Will your test use a lot of support equipment and/or personnel?

Chamber Facility's Role

- **Go through the process to schedule your test on the facility schedule**
  - **Do it as soon as you know a credible date**
  - **Make them aware of your schedule changes immediately**
- **The facility usually generates their own test procedure**
  - **Provide your test matrix including chamber condition requirements**
    - **Cryogenic cold targets**
    - **IR lamps**
    - **Solar simulation lamps**
    - **Test atmosphere (GN_2 is one typical medium)**
    - **Shroud temperature (level & rate of change)**
    - **Contamination monitors**
- **A facility dry-run of your test is highly recommended**
  - **Especially is chamber has been inoperative for some time**

Data Acquisition & Instrumentation (1/5)



- Data acquisition system
  - Does it have enough capacity?
    - Temperature channels & power supply telemetry
  - Does it meet your data sampling needs?
    - One entire scan every minutes is usually sufficient
  - Can it perform computations with raw test data?
  - Can it display you data in digital (time-slice) & analog (plot) form?
  - Does it have telemetry alarms (red & yellow)?
  - Provide the data acquisition support group a comprehensive list:
    - Temperature sensors (total number, type, location, alarm limits)
    - Heaters (total number, power, resistance, location, alarm limits)
    - Computed data (formulae)
    - Data display preference (grouping of telemetry for digital or analog display)

Data Acquisition & Instrumentation (2/5)

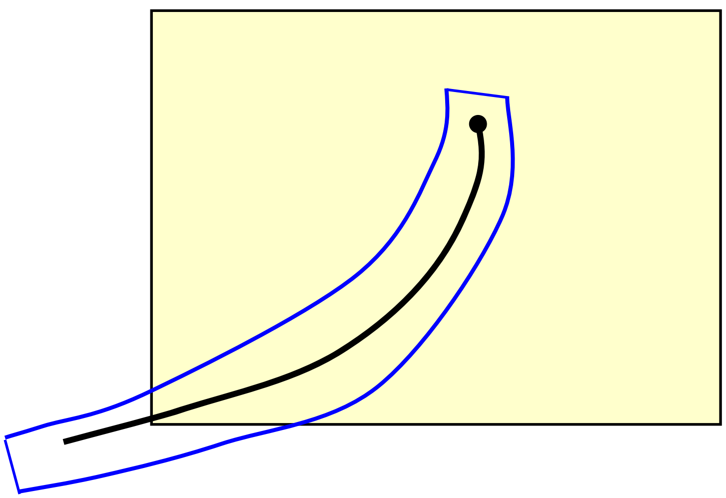
- **Temperature instrumentation**
  - **Developing a detailed location map using drawings & photos is essential**
  - **Thermocouple type: Type E, 26 AWG**
    - **Chromel/Constantan recommended to maximize temperature/voltage sensitivity & to minimize parasitic heat leak**
    - **Smaller gauge wire may be needed for very low thermal balance cases**
      - These thermocouples are more susceptible to breakage
  - **Consider redundant thermocouples in critical situations**
    - **Avoid the need for a chamber break in an event of a failure**
  - **Provide sufficient lead time for the installation of thermocouples that are buried inside hardware assemblies**
    - **May result in "clip & fly" approach; may need to consider shielding or grounding open thermocouple**
  - **Place a test thermocouple on every test heater & have its telemetry visible**
  - **For external surface thermocouples, use tape to match actual surface emittance**

Data Acquisition & Instrumentation (2/5)

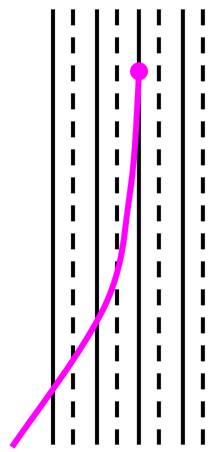
- **Yellow & Red Alarms**
  - As a rule of thumb, flight hardware must be maintained within any previous test experience
    - PF/QUAL/FA levels apply
    - Not applicable to PF/QUAL testing OR non-flight thermal control models or mock-ups
  - Yellow alarms are generally established as a “warning”
    - Approaching a “hard” limit & intervention by the thermal test engineer may be required to avoid exceedance
    - Particularly useful for thermally isolated & low mass items
  - Red alarms are generally defined as “never-to-exceed”
    - FA test level usually apply to flight hardware undergoing system test

Data Acquisition & Instrumentation (3/5)

- **Thermocouples locally disturb flight-like thermal balance**
  - **Complicates accurate measurement for low heat flow situation (e.g., thermal blankets)**
  - **Minimize non-flight features to the maximum extent practical**



If mounted on an exterior surface, thermally sink thermocouple wire to exterior surface & match exterior surface emittance



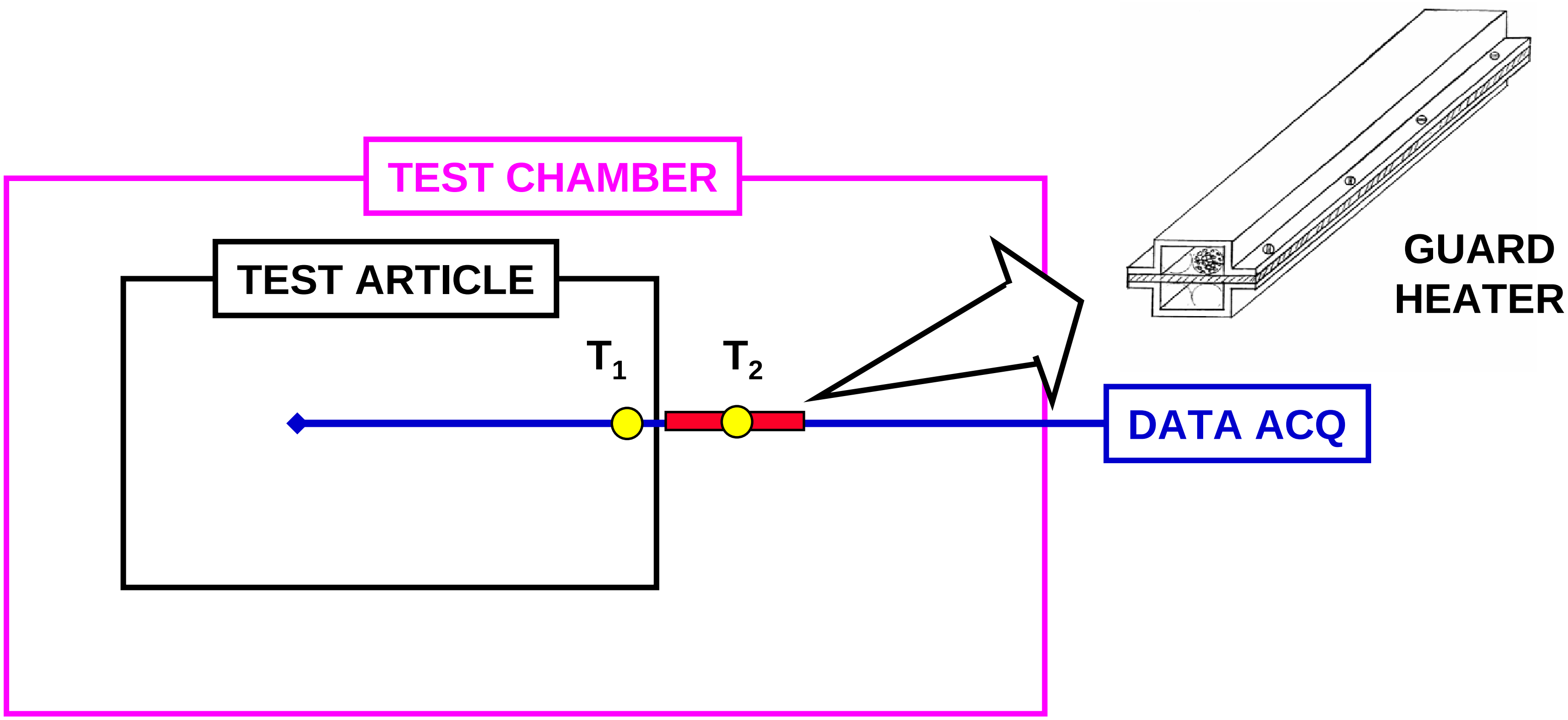
If the blanket is non-flight, attach thermocouple to 2nd or 3rd inner layer & route maximum length of wire inside blanket

Data Acquisition & Instrumentation (4/5)

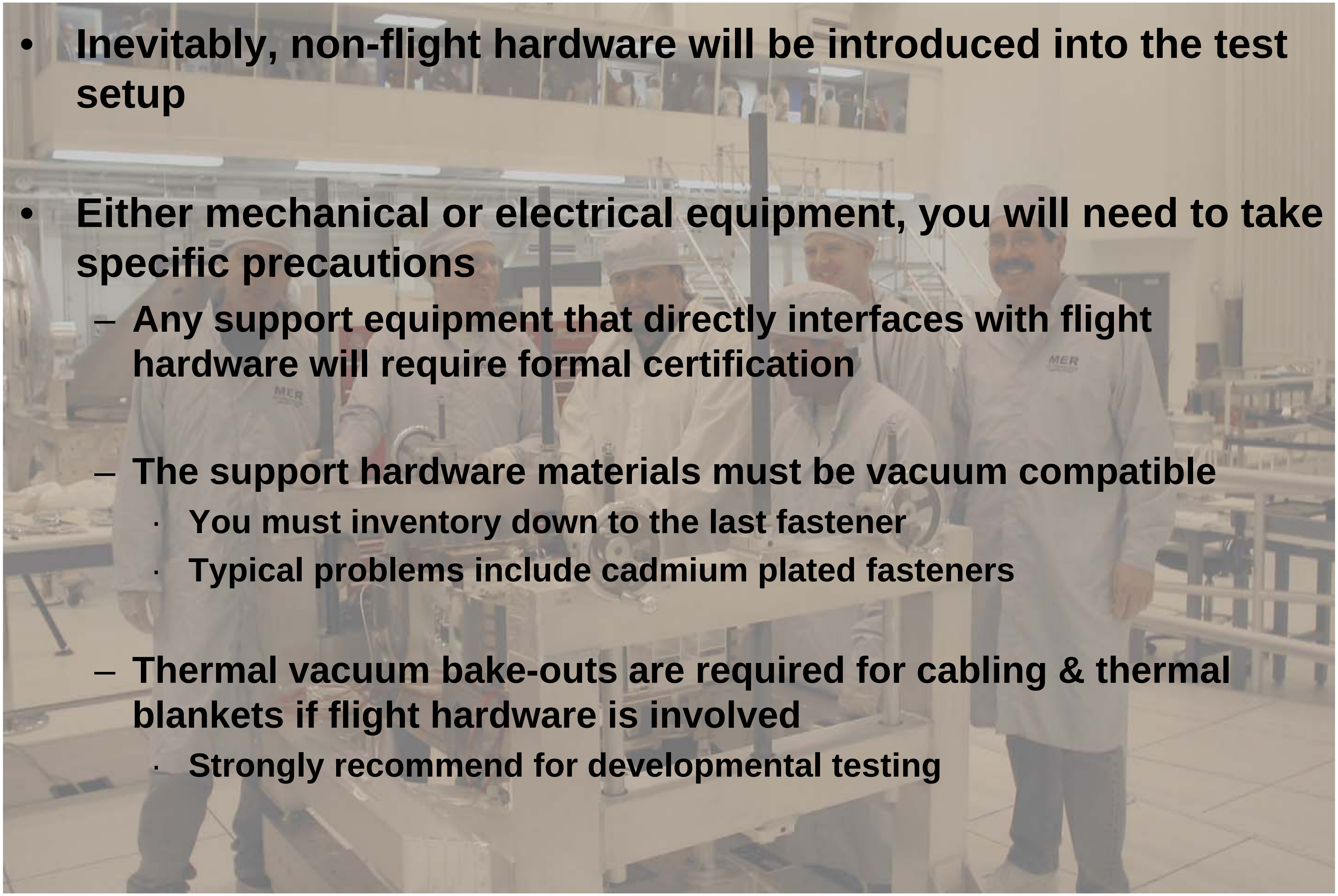
- **Heater instrumentation**
  - Use a 4.0 watt/in^2 guideline for maximum heater power density without special heat sinking provisions
    - This is a recommended maximum value when installing test heaters on flight hardware
  - Use test safety or acceleration heaters
  - Heater lead wire should accommodate worst-case current draw
  - Explicitly use current and/or voltage limit every power supply regardless of soft crow-bar
    - Avoid reliance upon soft crow-bars
  - Do you need guard heaters for instrumentation cabling?

Data Acquisition & Instrumentation (5/5)

- **Cabling guard heater implementation**
  - The objective is to reduce loss from cabling to chamber
  - This is accomplished by controlling the local heat flow where cabling egresses from test article
  - Apply heater power to guard heater so that $T_1 \approx T_2$



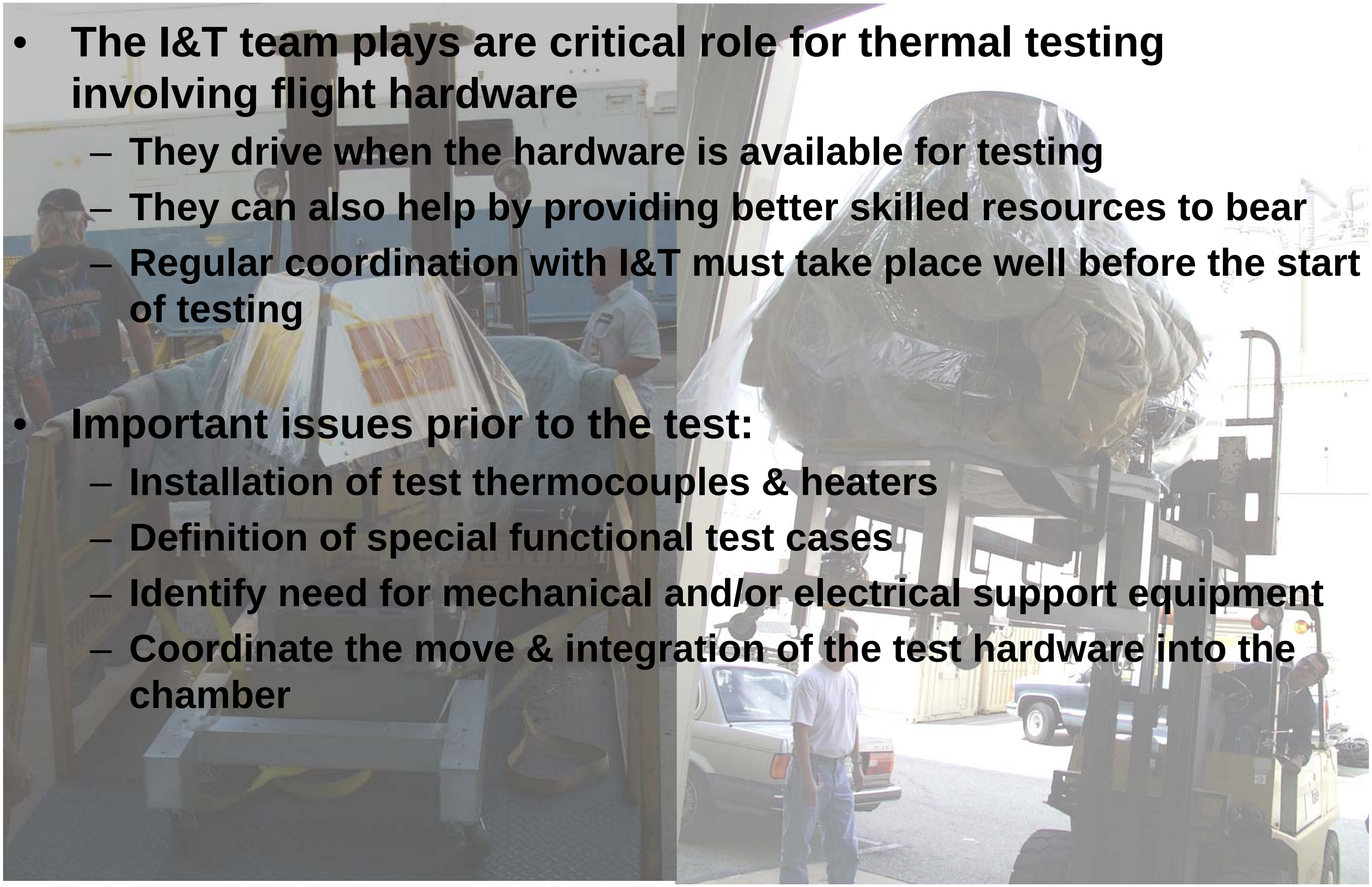
Mechanical & Electrical Support Equipment



- **Inevitably, non-flight hardware will be introduced into the test setup**

- **Either mechanical or electrical equipment, you will need to take specific precautions**
  - **Any support equipment that directly interfaces with flight hardware will require formal certification**
  - **The support hardware materials must be vacuum compatible**
    - **You must inventory down to the last fastener**
    - **Typical problems include cadmium plated fasteners**
  - **Thermal vacuum bake-outs are required for cabling & thermal blankets if flight hardware is involved**
    - **Strongly recommend for developmental testing**

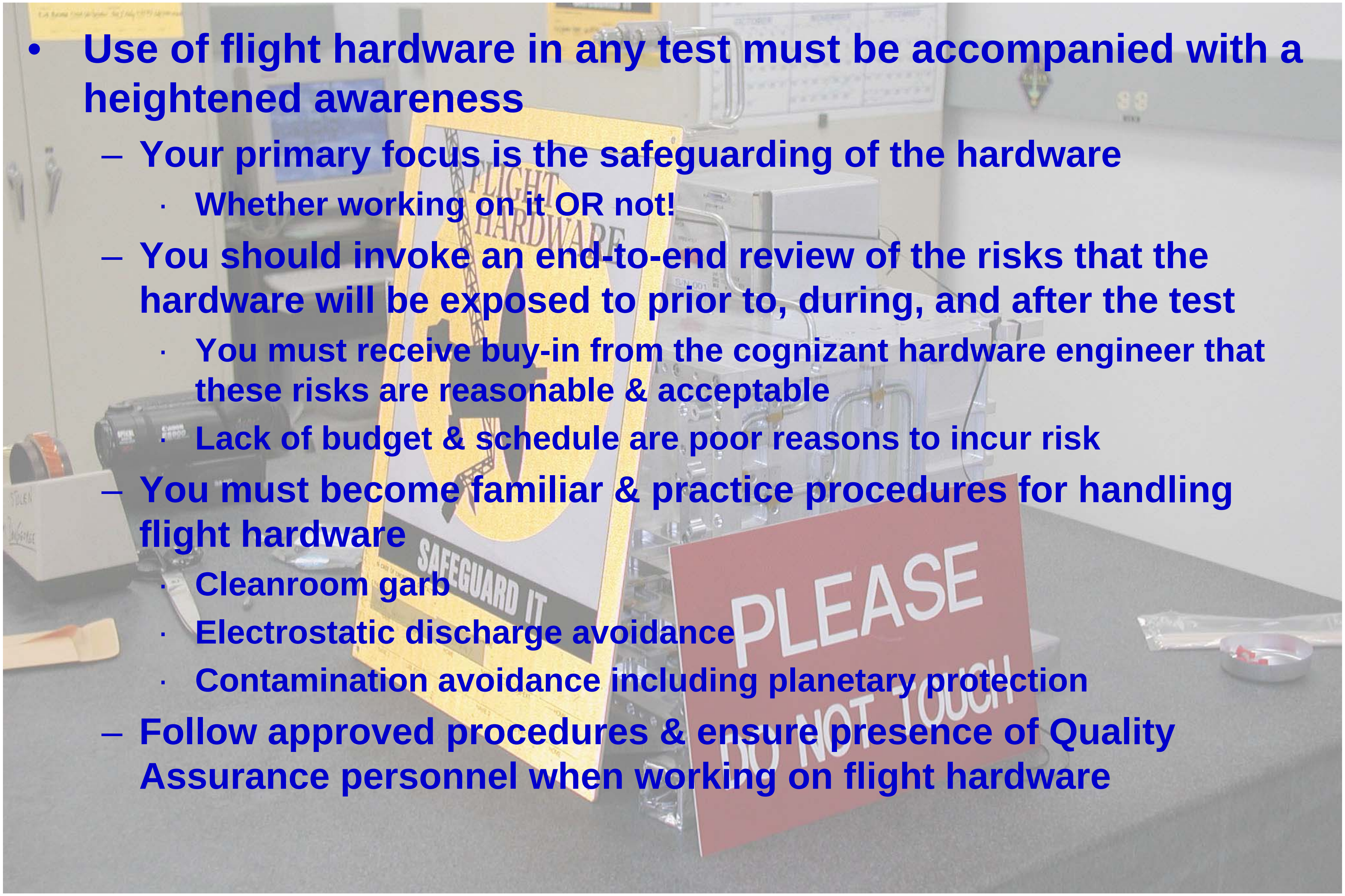
Interfacing with Integration & Test



- **The I&T team plays are critical role for thermal testing involving flight hardware**
  - **They drive when the hardware is available for testing**
  - **They can also help by providing better skilled resources to bear**
  - **Regular coordination with I&T must take place well before the start of testing**

- **Important issues prior to the test:**
  - **Installation of test thermocouples & heaters**
  - **Definition of special functional test cases**
  - **Identify need for mechanical and/or electrical support equipment**
  - **Coordinate the move & integration of the test hardware into the chamber**

Testing with Flight Hardware



- **Use of flight hardware in any test must be accompanied with a heightened awareness**
  - **Your primary focus is the safeguarding of the hardware**
    - **Whether working on it OR not!**
  - **You should invoke an end-to-end review of the risks that the hardware will be exposed to prior to, during, and after the test**
    - **You must receive buy-in from the cognizant hardware engineer that these risks are reasonable & acceptable**
    - **Lack of budget & schedule are poor reasons to incur risk**
  - **You must become familiar & practice procedures for handling flight hardware**
    - **Cleanroom garb**
    - **Electrostatic discharge avoidance**
    - **Contamination avoidance including planetary protection**
  - **Follow approved procedures & ensure presence of Quality Assurance personnel when working on flight hardware**

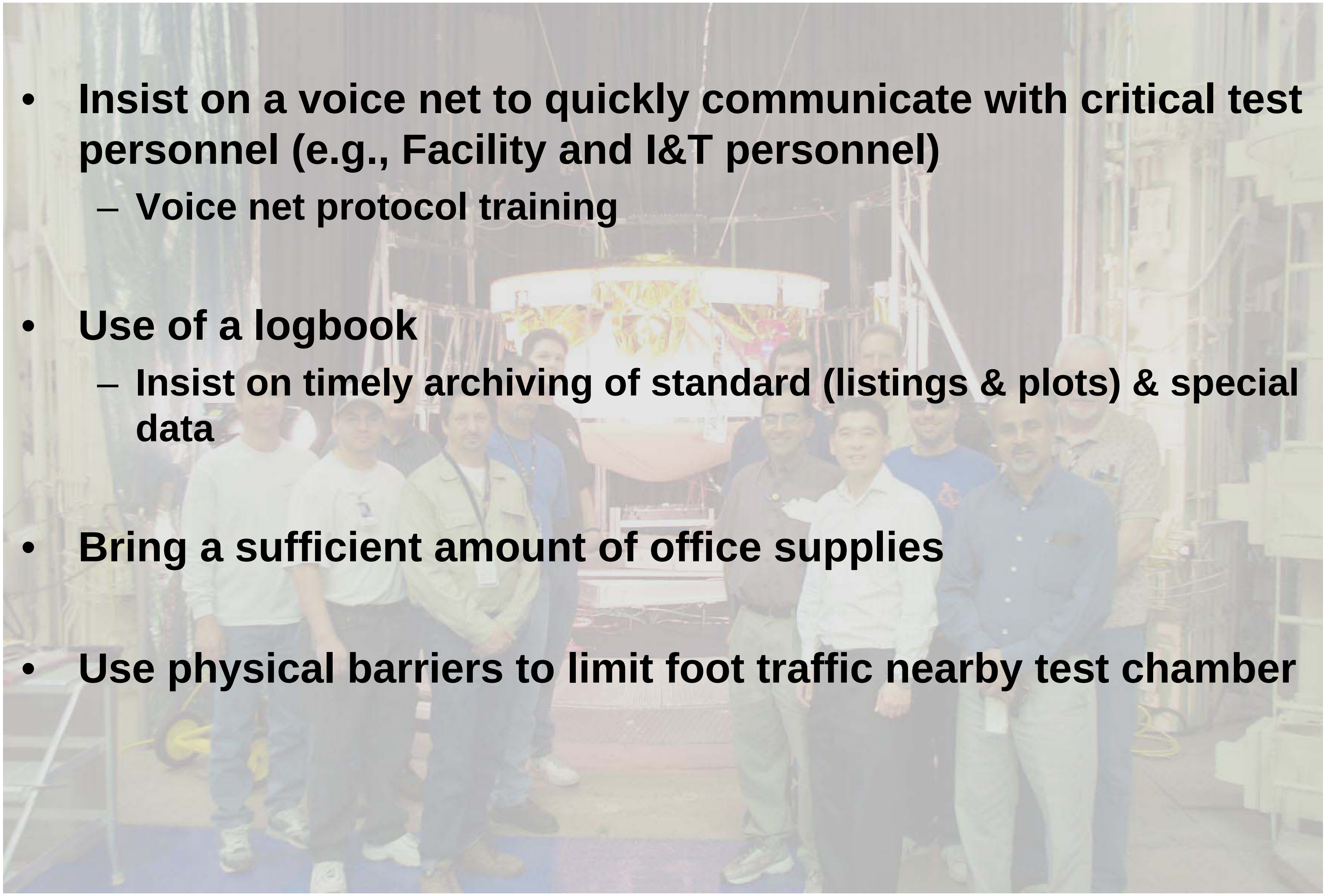
Safety First!

- **Your other primary focus must be the safety of everyone involved with your test**
  - **Is the test facility certified?**
    - **Consider support equipment such as cranes or other hoisting devices**
  - **Is your test staffing adequately trained to perform their functions?**
    - **"Buddy" system usage**
    - **Entry into confined spaces**
    - **Entry into spaces where GN_2 or LN_2 was used**
  - **Has test plan/procedure been survey & approved by Safety?**
    - **Emergency evacuation procedures**
    - **Emergency contact information**
    - **Loss of facility power procedures**
    - **Loss of data acquisition procedure**
    - **Loss of facility vacuum procedure**

Considerations For Executing the Test (1/2)

- Use an optimal test matrix strategy
  - Rule of Thumb: First test case should be coldest environment & then subsequent case are incrementally warmer
  - Rule of Thumb for critical events: Avoid scheduling critical events during the graveyard shift
  - Use a system engineering approach to all functional verification or validation aspects of the thermal design
  - Seek out input from hardware cognizant engineer or I&T engineers for recommendations for special tests
- Balanced monitoring workforce to prevent mistakes
  - Rule of Thumb for around-the-clock testing: 3 shifts with 2 test monitors for a 9-hour duration with an overlap of 1 hour between shifts for a hand-over briefing
  - Provide monitoring relief after 5 consecutive days
- Ensure your monitoring staff has adequate data acquisition training
- Verify that your test instrumentation, including flight telemetry, is functional prior to chamber door closing

Considerations For Executing the Test (2/2)



- Insist on a voice net to quickly communicate with critical test personnel (e.g., Facility and I&T personnel)
  - Voice net protocol training
- Use of a logbook
  - Insist on timely archiving of standard (listings & plots) & special data
- Bring a sufficient amount of office supplies
- Use physical barriers to limit foot traffic nearby test chamber

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